REPORT #
RRTAC 88-10

Review Of Literature Related To Clay Liners For Sump Disposal Of Drilling Waste

Heritage Fund

Alberta

LAND CONSERVATION AND
RECLAMATION COUNCIL
Reclamation Research
Technical Advisory Committee

Report No. RRTAC 88-10

Review of Literature Related to Clay Liners For Sump Disposal of Drilling Waste

by

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for

The Oil and Gas Reclamation Research Progam

of the

ALBERTA LAND CONSERVATION AND RECLAMATION COUNCIL
(Reclamation Research Technical Advisory Committee)

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The recommendations and conclusions in this report are those of the author and not of the Alberta Government or its representatives.

This report is intended to provide government and industry staff with up-to-date technical information to assist in the preparation and review of Development and Reclamation Approvals, and development of guidelines and operating procedures. This report is also available to the public so that interested individuals similarly have access to the most current information on land reclamation topics.

ALBERTA'S RECLAMATION RESEARCH PROGRAM

Regulating surface disturbances in Alberta is the responsibility of the Land Conservation and Reclamation Council. The Council executive consists of a Chairman from Alberta Environment and two deputy chairmen from Alberta Forestry, Lands and Wildlife. The Council oversees a reclamation research program, established in 1978, to identify the most efficient methods for achieving acceptable reclamation in the province. Funding for the research program is provided by Alberta's Heritage Savings Trust Fund Land Reclamation Program.

To assist with development and administration of the research program, the Council appointed the interdepartmental Reclamation Research Technical Advisory Committee (RRTAC). The Committee consists of eight members representing the Alberta Departments of Agriculture, Forestry, Lands and Wildlife, and, Environment, and the Alberta Research Council. The Committee updates research priorities, reviews solicited and unsolicited research proposals, organizes workshops, and otherwise acts as the coordinating body for reclamation research in Alberta.

Additional information on the Reclamation Research Program may be obtained by contacting:

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RECLAMATION RESEARCH REPORTS

** 1. RRTAC 80-3: The Role of Organic Compounds in Salinization of Plains Coal Mining Sites. N.S.C. Cameron et al. 46 pp.

DESCRIPTION: This is a literature review of the chemistry of sodic mine spoil and the changes expected to occur in groundwater.

** 2. RRTAC 80-4: Proceedings: Workshop on Reconstruction of Forest Soils in Reclamation. P.F. Ziemkiewicz, S.K. Takyi, and H.F. Regier. 160 pp.

DESCRIPTION: Experts in the field of forestry and forest soils report on research relevant to forest soil reconstruction and discuss the most effective means of restoring forestry capability of mined lands.

N/A 3. RRTAC 80-5: Manual of Plant Species Suitability for Reclamation in Alberta. L.E. Watson, R.W. Parker, and D.F. Polster. 2 vols, 541 pp.

DESCRIPTION: Forty-three grass, fourteen forb, and thirty-four shrub and tree species are assessed in terms of their suitability for use in reclamation. Range maps, growth habit, propagation, tolerance, and availability information are provided.

N/A 4. RRTAC 81-2: 1980 Survey of Reclamation Activities in Alberta. D.G. Walker and R.L. Rothwell. 76 pp.

DESCRIPTION: This survey is an update of a report prepared in 1976 on reclamation activities in Alberta, and includes research and operational reclamation, locations, personnel, etc.

N/A 5. RRTAC 81-3: Proceedings: Workshop on Coal Ash and Reclamation. P.F. Ziemkiewicz, R. Stein, R. Leitch, and G. Lutwick. 253 pp.

DESCRIPTION: Presents nine technical papers on the chemical, physical, and engineering properties of Alberta fly and bottom ashes, revegetation of ash disposal sites, and use of ash as a soil amendment. Workshop discussions and summaries are also included.

N/A 6. RRTAC 82-1: Land Surface Reclamation: An International Bibliography. H.P. Sims and C.B. Powter. 2 vols, 292 pp.

DESCRIPTION: Literature to 1980 pertinent to reclamation in Alberta is listed in Vol. 1 and is also on the University of Alberta computing system (in a SPIRES database called RECLAIM). Vol. 2 comprises the keyword index and computer access manual.

N/A 7. RRTAC 82-2: A Bibliography of Baseline Studies in Alberta: Soils, Geology, Hydrology, and Groundwater. C.B. Powter and H.P. Sims. 97 pp.

DESCRIPTION: This bibliography provides baseline information for persons involved in reclamation research or in the preparation of environmental impact assessments. Materials, up to date as of December 1981, are available in the Alberta Environment Library.

N/A 8. RRTAC 83-1: Soil Reconstruction Design for Reclamation of Oil Sand Tailings. Monenco Consultants Ltd. 185 pp.

DESCRIPTION: Volumes of peat and clay required to amend oil sand tailings were estimated based on existing literature. Separate soil prescriptions were made for spruce, jack pine, and herbaceous cover types. The estimates form the basis of field trials.

N/A 9. RRTAC 83-3: Evaluation of Pipeline Reclamation Practices on Agricultural Lands in Alberta. Hardy Associates (1978) Ltd. 205 pp.

DESCRIPTION: Available information on pipeline reclamation practices was reviewed. A field survey was then conducted to determine the effects of pipe size, age, soil type, construction method, etc. on resulting crop production.

N/A 10. RRTAC 83-4: Proceedings: Effects of Coal Mining on Eastern Slopes Hydrology. P.F. Ziemkiewicz. 123 pp.

DESCRIPTION: Technical papers are presented dealing with the impacts of mining on mountain watersheds, their flow characteristics, and resulting water quality. Mitigative measures and priorities were also discussed.

N/A 11. RRTAC 83-5: Woody Plant Establishment and Management for Oil Sands Mine Reclamation. Techman Engineering Ltd. 124 pp.

DESCRIPTION: This is a review and analysis of information on planting stock quality, rearing techniques, site preparation, planting, and procedures necessary to ensure survival of trees and shrubs in oil sand reclamation.

*** 12. RRTAC 84-1: Land Surface Reclamation: A Review of the International Literature. H.P. Sims, C.B. Powter, and J.A. Campbell. 2 vols, 1549 pp.

DESCRIPTION: Nearly all topics of interest to reclamationists including mining methods, soil amendments, revegetation, propagation and toxic materials are reviewed in light of the international literature.

** 13. RRTAC 84-2: Propagation Study: Use of Trees and Shrubs for Oil Sand Reclamation. Techman Engineering Ltd. 58 pp.

DESCRIPTION: This report evaluates and summarizes all available published and unpublished information on large-scale propagation methods for shrubs and trees to be used in oil sand reclamation.

* 14. RRTAC 84-3: Reclamation Research Annual Report - 1983. P.F. Ziemkiewicz. 42 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

** 15. RRTAC 84-4: Soil Microbiology in Land Reclamation. D. Parkinson, R.M. Danielson, C. Griffiths, S. Visser, and J.C. Zak. 2 vols, 676 pp.

DESCRIPTION: This is a collection of five reports dealing with re-establishment of fungal decomposers and mycorrhizal symbionts in various amended spoil types.

** 16. RRTAC 85-1: Proceedings: Revegetation Methods for Alberta's Mountains and Foothills. P.F. Ziemkiewicz. 416 pp.

DESCRIPTION: Results of long-term experiments and field experience on species selection, fertilization, reforestation, topsoiling, shrub propagation and establishment are presented.

* 17. RRTAC 85-2: Reclamation Research Annual Report - 1984. P.F. Ziemkiewicz. 29 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

** 18. RRTAC 86-1: A Critical Analysis of Settling Pond Design and Alternative Technologies. A. Somani. 372 pp.

DESCRIPTION: The report examines the critical issue of settling pond design, and sizing and alternative technologies. The study was co-funded with The Coal Association of Canada.

** 19. RRTAC 86-2: Characterization and Variability of Soil Reconstructed after Surface Mining in Central Alberta. T.M. Macyk. 146 pp.

DESCRIPTION: Reconstructed soils representing different materials handling and replacement techniques were characterized, and variability in chemical and physical properties was assessed. The data obtained indicate that reconstructed soil properties are determined largely by parent material characteristics and further tempered by materials handling procedures. Mining tends to create a relatively homogeneous soil landscape in contrast to the mixture of diverse soils found before mining.

* 20. RRTAC 86-3: Generalized Procedures for Assessing Post-Mining Groundwater Supply Potential in the Plains of Alberta - Plains Hydrology and Reclamation Project. M.R. Trudell and S.R. Moran. 30 pp.

DESCRIPTION: In the Plains region of Alberta, the surface mining of coal generally occurs in rural, agricultural areas in which domestic water supply requirements are met almost entirely by groundwater. Consequently, an important aspect of the capability of reclaimed lands to satisfy the needs of a residential component is the post-mining availability of groundwater. This report proposes a sequence of steps or procedures to identify and characterize potential post-mining aquifers.

** 21. RRTAC 86-4: Geology of the Battle River Site: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze, R. Li, M. Fenton and S.R. Moran. 86 pp.

DESCRIPTION: This report summarizes the geological setting of the Battle River study site. It is designed to provide a general understanding of geological conditions adequate to establish a framework for hydrogeological and general reclamation studies. The report is not intended to be a detailed synthesis such as would be required for mine planning purposes.

** 22. RRTAC 86-5: Chemical and Mineralogical Properties of Overburden: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze. 71 pp.

DESCRIPTION: This report describes the physical and mineralogical properties of overburden materials in an effort to identify individual beds within the bedrock overburden that might be significantly different in terms of reclamation potential.

* 23. RRTAC 86-6: Post-Mining Groundwater Supply at the Battle River Site: Plains Hydrology and Reclamation Project. M.R. Trudell, G.J. Sterenberg and S.R. Moran. 49 pp.

DESCRIPTION: The report deals with the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations. The study area is in the Battle River Mining area in east-central Alberta

* 24. RRTAC 86-7: Post-Mining Groundwater Supply at the Highvale Site: Plains Hydrology and Reclamation Project. M.R. Trudell. 25 pp.

DESCRIPTION: This report evaluates the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations. The study area is the Highvale mining area in west-central Alberta.

* 25. RRTAC 86-8: Reclamation Research Annual Report - 1985. P.F. Ziemkiewicz. 54 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

** 26. RRTAC 86-9: Wildlife Habitat Requirements and Reclamation Techniques for the Mountains and Foothills of Alberta. J.E. Green, R.E. Salter and D.G. Walker. 285 pp.

DESCRIPTION: This report presents a review of relevant North American literature on wildlife habitats in mountain and foothills biomes, reclamation techniques, potential problems in wildlife habitat reclamation, and potential habitat assessment methodologies. Four biomes (Alpine, Subalpine, Montane, and Boreal Uplands) and 10 key wildlife species (snowshoe hare, beaver, muskrat, elk, moose, caribou, mountain goat, bighorn sheep, spruce grouse, and white-tailed ptarmigan) are discussed. The study was co-funded with The Coal Association of Canada.

** 27. RRTAC 87-1: Disposal of Drilling Wastes. L.A. Leskiw, E. Reinl-Dwyer, T.L. Dabrowski, B.J. Rutherford and H. Hamilton. 210 pp.

DESCRIPTION: Current drilling waste disposal practices are reviewed and criteria in Alberta guidelines are assessed. The report also identifies research needs and indicates mitigation measures. A manual provides a decision-making flowchart to assist in selecting methods of environmentally safe waste disposal.

** 28. RRTAC 87-2: Minesoil and Landscape Reclamation of the Coal Mines in Alberta's Mountains and Foothills. A.W. Fedkenheuer, L.J. Knapik and D.G. Walker. 174 pp.

DESCRIPTION: This report reviews current reclamation practices with regard to site and soil reconstruction and re-establishment of biological productivity. It also identifies research needs in the Mountain-Foothills area. The study was co-funded with The Coal Association of Canada.

** 29. RRTAC 87-3: Gel and Saline Drilling Wastes in Alberta: Workshop Proceedings. D.A. Lloyd (compiler). 218 pp.

DESCRIPTION: Technical papers were presented which describe: mud systems used and their purpose; industrial constraints; government regulations, procedures and concerns; environmental considerations in waste disposal; and toxic constituents of drilling wastes. Answers to a questionnaire distributed to participants are included in an appendix.

* 30. RRTAC 87-4: Reclamation Research Annual Report - 1986. 50 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

* 31. RRTAC 87-5: Review of the Scientific Basis of Water Quality Criteria for the East Slope Foothills of Alberta. Beak Associates Consulting Ltd. 46 pp.

DESCRIPTION: The report reviews existing Alberta guidelines to assess the quality of water drained from coal mine sites in the East Slope Foothills of Alberta. World literature was reviewed within the context of the East Slopes environment and current mining operations. The ability of coal mine operators to meet the various guidelines is discussed. The study was co-funded with The Coal Association of Canada.

** 32. RRTAC 87-6: Assessing Design Flows and Sediment Discharge on the Eastern Slopes. Hydrocon Engineering (Continental) Ltd. and Monenco Consultants Ltd. 97 pp.

DESCRIPTION: The report provides an evaluation of current methodologies used to determine sediment yields due to rainfall events in well-defined areas. Models are available in Alberta to evaluate water and sediment discharge in a post-mining situation. SEDIMOT II (Sedimentology Disturbed Modelling Techniques) is a single storm model that was developed specifically for the design of sediment control structures in watersheds disturbed by surface mining and is well suited to Alberta conditions. The study was co-funded with The Coal Association of Canada.

* 33. RRTAC 87-7: The Use of Bottom Ash as an Amendment to Sodic Spoil. S. Fullerton. 83 pp.

DESCRIPTION: The report details the use of bottom ash as an amendment to sodic coal mine spoil. Several rates and methods of application of bottom ash to sodic spoil were tested to determine which was the best at reducing the effects of excess sodium and promoting crop growth. Field trials were set up near the Vesta mine in East Central Alberta using ash readily available from a nearby coal-fired thermal generating station. The research indicated that bottom ash incorporated to a depth of 30 cm using a subsoiler provided the best results.

* 34. RRTAC 87-8: Waste Dump Design for Erosion Control. R.G. Chopiuk and S.E. Thornton. 45 pp.

DESCRIPTION: This report describes a study to evaluate the potential influence of erosion from reclaimed waste dumps on downslope environments such as streams and rivers. Sites were selected from coal mines in Alberta's mountains and foothills, and included resloped dumps of different configurations and ages, and having different vegetation covers. The study concluded that the average annual amount of surface erosion is minimal. As expected, erosion was greatest on slopes which were newly regraded. Slopes with dense grass cover showed no signs of erosion. Generally, the amount of erosion decreased with time, as a result of initial loss of fine particles, the formation of a weathered surface, and increased vegetative cover.

** 35. RRTAC 87-9: Hydrogeology and Groundwater Chemistry of the Battle River Mining Areas. M.R. Trudell, R.L. Faught and S.R. Moran. 97 pp.

DESCRIPTION: This report describes the premining geologic conditions in the Battle River coal mining area including the geology as well as the groundwater flow patterns, and the groundwater quality of a sequence of several water-bearing formations extending from the surface to a depth of about 100 metres.

** 36. RRTAC 87-10: Soil Survey of the Plains Hydrology and Reclamation Project - Battle River Project Area. T.M. Macyk and A.H. MacLean. 62 pp. plus 8 maps.

DESCRIPTION: The report evaluates the capability of post-mining landscapes and assesses the changes in capability as a result of mining, in the Battle River mining area. Detailed soils information is provided in the report for lands adjacent to areas already mined as well as for lands that are destined to be mined. Characterization of the reconstructed soils in the reclaimed areas is also provided. Data were collected from 1979 to 1985. Eight maps supplement the report.

** 37. RRTAC 87-11: Geology of the Highvale Study Site: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze. 78 pp.

DESCRIPTION: The report is one of a series that describes the geology, soils and groundwater conditions at the Highvale Coal Mine study site. The purpose of the study was to establish a summary of site geology to a level of detail necessary to provide a framework for studies of hydrogeology and reclamation.

** 38. RRTAC 87-12: Premining Groundwater Conditions at the Highvale Site. M.R. Trudell and R. Faught. 83 pp.

DESCRIPTION: This report presents a detailed discussion of the premining flow patterns, hydraulic properties, and isotopic and hydrochemical characteristics of five layers within the Paskapoo Geological Formation, the underlying sandstone beds of the Upper Horseshoe Canyon Formation, and the surficial glacial drift.

* 39. RRTAC 87-13: An Agricultural Capability Rating System for Reconstructed Soils. T.M. Macyk. 27 pp.

DESCRIPTION: This report provides the rationale and a system for assessing the agricultural capability of reconstructed soils. Data on the properties of the soils used in this report are provided in RRTAC 86-2.

** 40. RRTAC 88-1: A Proposed Evaluation System for Wildlife Habitat Reclamation in the Mountains and Foothills Biomes of Alberta: Proposed Methodology and Assessment Handbook. T.R. Eccles, R.E. Salter and J.E. Green. 101 pp. plus appendix.

DESCRIPTION: The report focuses on the development of guidelines and procedures for the assessment of reclaimed wildlife habitat in the Mountains and Foothills regions of Alberta. The technical section provides background documentation including a discussion of reclamation planning, a listing of reclamation habitats and associated key wildlife species, conditions required for development, recommended revegetation species, suitable reclamation techniques, a description of the recommended assessment techniques and a glossary of basic terminology. The assessment handbook section contains basic information necessary for evaluating wildlife habitat reclamation, including assessment scoresheets for 15 different reclamation habitats, standard methodologies for measuring habitat variables used as assessment criteria, and minimum requirements for certification. This handbook is intended as a field manual that could potentially be

used by site operators and reclamation officers. The study was co-funded with The Coal Association of Canada.

** 41. RRTAC 88-2: Plains Hydrology and Reclamation Project: Spoil Groundwater Chemistry and its Impacts on Surface Water. M.R. Trudell (compiler). 135 pp.

DESCRIPTION: Two reports comprise this volume. The first "Chemistry of Groundwater in Mine Spoil, Central Alberta," describes the chemical make-up of spoil groundwater at four mines in the Plains of Alberta. It explains the nature and magnitude of changes in groundwater chemistry following mining and reclamation. The second report, "Impacts of Surface Mining on Chemical Quality of Streams in the Battle River Mining Area," describes the chemical quality of water in streams in the Battle River mining area, and the potential impact of groundwater discharge from surface mines on these streams.

** 42. RRTAC 88-3: Revegetation of Oil Sands Tailings: Growth Improvement of Silver-berry and Buffalo-berry by Inoculation with Mycorrhizal Fungi and N_2-Fixing Bacteria. S. Visser and R.M. Danielson. 98 pp.

DESCRIPTION: The report provides results of a study: (1) To determine the mycorrhizal affinities of various actinorrhizal shrubs in the Fort McMurray, Alberta region; (2) To establish a basis for justifying symbiont inoculation of buffalo-berry and silver-berry; (3) To develop a growing regime for the greenhouse production of mycorrhizal, nodulated silver-berry and buffalo-berry; and, (4) To conduct a field trial on reconstructed soil on the Syncrude Canada Limited oil sands site to critically evaluate the growth performance of inoculated silver-berry and buffalo-berry as compared with their uninoculated counterparts.

** 43. RRTAC 88-4: Plains Hydrology and Reclamation Project: Investigation of the Settlement Behaviour of Mine Backfill. D.R. Pauls (compiler). 135 pp.

DESCRIPTION: This three part volume covers the laboratory assessment of the potential for subsidence in reclaimed landscapes. The first report in this volume, "Simulation of Mine Spoil Subsidence by Consolidation Tests," covers laboratory simulations of the subsidence process particularly as it is influenced by resaturation of mine spoil. The second report, "Water Sensitivity of Smectitic Overburden: Plains Region of Alberta," describes a series of laboratory tests to determine the behaviour of overburden materials when brought into contact with water. The report entitled "Classification System for Transitional Materials: Plains Region of Alberta," describes a lithological classification system developed to address the characteristics of the smectite rich, clayey transition materials that make up the overburden in the Plains of Alberta.

** 44. RRTAC 88-5: Ectomycorrhizae of Jack Pine and Green Alder: Assessment of the Need for Inoculation, Development of Inoculation Techniques and Outplanting Trials on Oil Sand Tailings. R.H. Danielson and S. Visser. 177 pp.

DESCRIPTION: The overall objective of this research was to characterize the mycorrhizal status of Jack Pine and Green Alder which are prime candidates as reclamation species for oil sand tailings and to determine the potential benefits of mycorrhizae on plant performance. This entailed determining the symbiont status of container-grown nursery stock and the quantity and quality of inoculum in reconstructed soils, developing inoculation techniques and finally, performance testing in an actual reclamation setting.

* 45. RRTAC 88-6: Reclamation Research Annual Report - 1987. Reclamation Research Technical Advisory Committee. 67 pp.

DESCRIPTION: This annual report describes the expenditure of $500,000.00 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program.

* 46. RRTAC 88-7: Baseline Growth Performance Levels and Assessment Procedure for Commercial Tree Species in Alberta's Mountains and Foothills. W.R. Dempster and Associates Ltd. 66 pp.

DESCRIPTION: Data on juvenile height development of lodgepole pine and white spruce from cut-over or burned sites in the Eastern Slopes of Alberta were used to define reasonable expectations of early growth performance as a basis for evaluating the success of reforestation following coal mining. Equations were developed predicting total seedling height and current annual height increment as a function of age and elevation. Procedures are described for applying the equations, with further adjustments for drainage class and aspect, to develop local growth performance against these expectations. The study was co-funded with The Coal Association of Canada.

** 47. RRTAC 88-8: Alberta Forest Service Watershed Management Field and Laboratory Methods. A.M.K. Nip and R.A. Hursey, Alberta Forest Service. 4 Sections, various pagings.

DESCRIPTION: Disturbances such as coal mines in the Eastern Slopes of Alberta have the potential for affecting watershed quality during and following mining. The collection of hydrometric, water quality and hydrometeorologic information is a complex task. A variety of instruments and measurement methods are required to produce a record of hydrologic inputs and outputs for a watershed basin. There is a growing awareness and recognition that standardization of data acquisition methods is required to ensure data comparability, and to allow comparison of data analyses. The purpose of this manual is to assist those involved in the field of data acquisition by outlining methods, practices and instruments which are reliable and recognized by the International Organization for Standardization.

** 48. RRTAC 88-9: Computer Analysis of the Factors Influencing Groundwater Flow and Mass Transport in a System Disturbed by Strip Mining. F.W. Schwartz and A.S. Crowe, SIMCO Groundwater Research Ltd.

DESCRIPTION: Work presented in this report demonstrates how a groundwater flow model can be used to study a variety of mining-related problems such as declining water levels in areas around the mine as a result of dewatering, and the development of high water tables

in spoil once resaturation is complete. This report investigates the role of various hydrogeological parameters that influence the magnitude, timing, and extent of water level changes during and following mining at the regional scale. The modelling approach described here represents a major advance on existing work.

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EXECUTIVE SUMMARY

The purpose of this report is to assess the effectiveness of geological containment of drilling waste in sumps by conducting a literature review and problem analysis. Three premises were identified at the outset of the study. The first was that disposal of drilling waste in sumps is likely to be a standard practice in parts of Alberta. Secondly, heavy-duty polyethylene liners and exotic clay materials are too expensive for use in most drilling-waste disposal sumps and finally that compacted indigenous clay liners will be used in most waste sumps.

A literature review was conducted in sources identified through a search of the GEOREF and NTIS data bases involving two combinations of keywords in each data base. One hundred and eleven references were identified for the period 1985-1987. Two particularly useful publications that were reviewed were, "Design, Construction, and Evaluation of Clay Liners for Waste Management Facilities", a comprehensive report prepared for the US EPA, and "An Evaluation of the Effects of Brine on a Compacted Clay Till Liner", a report prepared for Alberta Environment RMD. The Geotechnical Research Centre of the University of Western Ontario, which is internationally recognized for its expertise in contaminant transport studies in clayey materials, provided a number of additional reports based on current research.

The review indicated that glacial till throughout Alberta has similar properties and is generally well suited for construction of clay liners. Optimum liner characteristics of low initial permeability and low shrinkage are obtained with materials containing appreciable sand and by compacting at slightly above optimum water content. At the expected hydraulic conductivity of liners constructed of Alberta till materials, advective transport is expected to dominate over diffusion.

For the purpose of assessing hydraulic conductivity a constant-flow type permeameter appears to be the best testing

apparatus for laboratory determination of hydraulic conductivity. No definitive explanation has been advanced for the almost universally observed one to two order of magnitude difference between field and laboratory determinations of hydraulic conductivity of compacted clay liners.

Smectitic clays, such as are common in Alberta, experience an increase in permeability in contact with hypersaline and organic permeants. Laboratory studies of smectitic clays in solutions containing high concentrations of potassium ion have demonstrated severe shrinkage. Field studies of interactions between hypersaline fluids and clay liners have focused on sodium; we found no field studies of permeability characteristics of liners exposed to high concentrations of potassium ion.

Organic permeants with low-dielectric constants tend to increase permeability by inducing shrinkage, but commonly give misleading or erroneous results in laboratory tests because of their hydrophobic nature and low solubility in water. Attenuation of sodium, potassium, total dissolved solids, total organic carbon, and heavy metals, although difficult to quantify, appears to increase with increasing cation exchange capacity of the liner.

Classification of clay liner characteristics and waste composition should precede design of individual facilities because interactions between the two are not straightforward.

It is recommended that a scientific study be conducted to investigate the chemical and structural factors in construction and performance of clay liners composed of Alberta till. The study should further evaluate the effects of interactions of the various chemical constituents of drilling wastes with the liner material on the long-term permeability of the clay liners.

In addition, an expert system should be developed to access the exhaustive body of knowledge on the interactions between different types of clay liners and various specific permeants to allow prediction of the behaviour of a particular clay with a particular suite of drilling-waste constituents. Such a system would

allow assessment of environmental sensitivity of a proposed sump site, optimum liner design, and assignment of quality control during construction.

It is also recommended that guidelines for construction of clay liners for drilling-waste disposal sumps should specify acceptable confidence limits within which parameters such as compaction water content, dry density, material variability, and hydraulic conductivity are allowed to vary, rather than identifying specific values for these parameters.

1. INTRODUCTION

The oil and gas industry in Alberta drills millions of metres of boreholes during exploration and recovery of energy resources each year. Approximately 0.5 m^3 of drilling fluid is required for each metre of borehole drilled resulting in about five million cubic metres or 30 million barrels of drilling waste produced in 1985 alone (Conlin and Claridge 1986). Not surprisingly, simply because of their sheer volume, the disposal of these wastes has become an environmental concern.

Three different types of drilling muds are presently in use in Alberta: (1) the freshwater bentonite-type muds are most common and least toxic; (2) KCl-type and NaCl-type muds are hypersaline and thus present a potential for salinizing drill sites; (3) invert emulsion muds containing as much as 50% oil are used in heavy oil recovery areas. Other waste materials such as organic chemicals and heavy metals may also be present in waste sumps. The composition of drilling waste is being thoroughly investigated as part of this project.

Procedures for disposal of drilling wastes generated on a lease vary depending on the volume of waste. If less than 6000 m^3 of drilling waste exist on a site, the waste is disposed on the lease by trenching, squeezing, and land spreading or burial of solids, and subsurface injection of supernatant liquid. If more than 6000 m^3 exists at a lease, then the quality of sludge must be assessed and treated to regulated standards before disposal off lease. Because of the considerable incentive to limit the volume of waste to 6000 m^3, wastes with high concentrations of certain constituents result (Conlin and Claridge 1986).

The Reclamation Research Technical Advisory Committee has initiated this research project to investigate the environmental impact of drilling wastes and to assess the present standards and procedures for disposal of these wastes.

2. OBJECTIVE

The general objective of this project was to provide a scientific basis for development of guidelines for drilling-mud-solids disposal that optimizes environmental safety and cost-effectiveness. Three subobjectives were identified, two of which are addressed and reported under separate cover (Macyk et al. 1987). The third subobjective, which is addressed in this report, was to conduct a literature review and problem analysis of the effectiveness of geological containment of drilling waste in sumps. Of particular importance to this study is determination of changes in properties of clay materials as a result of contact with highly saline brines containing various organic chemicals.

Terms of reference call for execution of a literature review to evaluate the potential for migration of drilling-waste components in earth materials. The review was to focus on three main bodies of literature:

1. Case studies that relate to actual experience with this type of waste material in field settings.
2. Experimental studies that address the impact of highly saline solutions and solutions containing various types of organic molecules on the hydraulic conductivity of earth materials.
3. Experimental studies that address attenuation of saline and organic contaminants by flow through various earth materials.

It was expected that the synthesized literature review would provide a basis to identify gaps in the information base needed to assess hydrogeological implications of sump disposal of drilling wastes in Alberta. It was further anticipated that an experimental design would be developed to address any such gaps that were found.

3. STUDY METHODS

A report on the effects of brine on compacted clay liners that was prepared in 1986 by Komex Consultants Limited for Research Management Division of Alberta Environment served as a starting point for our investigation (Conlin and Claridge 1986). Although the Conlin and Claridge report is concerned with brine pond liners and, therefore, has a somewhat different emphasis than our study, much of the literature that they reviewed is relevant to our investigation. Much of the most relevant literature that has appeared subsequent to their report has been examined. In addition, certain topics that were of greater importance to our investigation than to the Conlin and Claridge study, because of the fundamental differences in the two problems, were searched more exhaustively.

3.1 LITERATURE SEARCH

Literature which was procured from the four sources listed below, covered a range of information from international publications to very localized Alberta case studies.

1.	Computerized data bases checked:	
	Georef (1985-1987)	International Documents
	NTIS (1985-1987)	
2.	EPA Report (March 86)	USA Authority
3.	Publications from University of Western Ontario (1987)	Canadian Authority
4.	RMD Report (1986)	Alberta Situation

3.1.2 Computerized Data Base Search

The Georef and NTIS data bases were searched. The Georef data base is very large and includes papers from engineering, geochemistry, and geological disciplines. Most articles found in the Georef data base can easily be procured from libraries in Alberta. The NTIS data base is also very large, but focuses to a greater degree on government research in chemistry, civil engineering, and

environmental issues. These papers are also very easy to procure through the excellent NTIS mail service.

The papers procured from these data bases are heavy on the engineering and empirical studies of hydrophysical properties of clays. Much synthesis of information would need to be done to extract meaningful reviews from more scientific papers found in data bases such as chemical abstracts, Agricola and Environment Periodical Bibliography. This is outside the scope of this project.

The Georef and NTIS data bases were searched using two combinations of keywords. The first combination emphasized the engineering of clay liners. The following combination of keywords identified 16 papers from Georef:

Permeability <u>and</u> clay <u>and</u>	waste	<u>NOT</u>	stratigraphy
	salt		sedimentary
	seepage		tailings pond
	crack		waste
			cell
			disposal

Another search designed to focus on contaminant transport science and mechanisms, involved the following search on NTIS and identified 25 post-1985 references.

waste	<u>and</u> clay <u>and</u>	attenuation
contaminant		dispersion
saline		dilution
organic		adsorption
leachate		sorption
		advection
		diffusion
		ion exchange

Another 25 post-1985 articles were identified from the following combination on NTIS.

permeability and clay and waste
hydraulic conductivity contaminant
saline
organic
leachate

Finally, the Georef data base produced 45 1985-1987 papers from the following keyword combination:

dispersion and clay and waste
attenuation contaminant
dilution saline
adsorption organic
sorption leachate
advection
diffusion
sorption

3.1.3 Other Information Sources

The Geotechnical Research Centre of the University of Western Ontario was contacted for their expertise in contaminant transport studies. Many current reports and papers were collected from them.

A report prepared for the United States Environmental Protection Agency entitled "Design, Construction, and Evaluation of Clay Liners for Waste Management Facilities" was procured. It contained an extensive review of the state-of-the-art clay-chemical interactions and soil permeability.

Finally, a report to Alberta Environment on clay barrier interaction with saline solutions which includes case studies involving Alberta glacial till liner material and hypersaline drilling-mud solutions was reviewed.

4. OVERVIEW OF THE PROBLEM

Two primary methods are employed for ultimate disposal of drilling wastes: (1) land spreading; and (2) sump disposal. The characteristics of drilling wastes as they influence potential for land spreading is the focus of another component of the Alberta Research Council's study, which is reported separately (Macyk et al. 1987). This component of the project is focused on the second of these disposal methods, sump disposal.

In considering design criteria for sump disposal of any waste, the first decision to be made involves the degree to which siting the facility is to serve as the primary assurance of environmental protection as opposed to relying on engineering of the facility. If the option exists to select a site with desirable hydrogeological and geotechnical characteristics, very often the optimum combination of cost-effective and environmentally-safe containment can be achieved by emphasizing site selection. If, however, a facility must be constructed in a particular location, considerably higher levels of engineered containment may be required. In general, we consider it likely that the former case applies to the disposal of drilling wastes in larger, centralized and more permanent storage and disposal facilities. That is, we have assumed that a site can be made available where adequate containment of the wastes can be obtained through construction of a compacted liner composed of native clay.

Because synthetic liners, such as an 80 mil High Density Polyethylene (HDPE) liner, cost approximately twice as much as a one-metre thick compacted clay liner (Conlin and Claridge 1986), there is considerable incentive to use compacted native materials to build liners for excavated or embanked storage pits and sumps. Even where synthetic liners are used, it is likely that some sort of secondary system of confinement, which relies on compacted native materials, will be required.

In order to evaluate the effectiveness of sump liners constructed of compacted native material in containing drilling wastes in Alberta, the following points must be considered:

1. The types of clay materials available at a particular site for use in constructing a liner.
2. The liner compaction characteristics required to achieve optimum retardation of contaminant migration through the liner.
3. The measurement and quality control techniques necessary to assure that optimum compaction characteristics are known and actually achieved in construction.
4. The composition and nature of the drilling wastes to be placed in the sump.
5. The degree and nature of attenuation of the waste constituents by the liner material.
6. The nature of, and factors controlling, chemical and physical changes in the liner that lead to deterioration of its performance as a result of interactions between the waste and liner materials.

These six points serve as the basis for organizing the material in this report.

5. SUITABILITY OF CLAY MATERIALS IN ALBERTA FOR LINER CONSTRUCTION

Throughout most of Alberta, surficial materials consist of deposits of glaciers and associated lakes and rivers that were formed during the period from about 10 000 to 15 000 years before present. In some places, wind deposited silt or sand cap the surface; in other places, mixed alluvial deposits of rivers and streams occur at the surface; in still other places a veneer of alluvial fan and slope-wash sediment covers the surface. In some places, the veneer of surficial sediment is sufficiently thin that weakly cemented to uncemented bedrock of Cretaceous age is encountered within a few metres of the surface.

In general terms, all surficial sand, gravel, and coarse-grained, well-sorted silt deposits should be avoided in selecting a location for a sump and are unsuitable for construction of sump liners. The silty and clayey deposits of lakes may, in some places, afford adequate confinement for location of sumps. Compaction characteristics of these materials, however, are generally poor and construction is more difficult than with the glacial sediment, till. Bedrock units such as the Bearpaw and Lea Park (La Biche) Formations consist of a considerable thickness of clay shale and generally provide suitable sites for location of disposal sumps. However, more plastic soils of the bedrock units and glaciolacustrine deposits are more susceptible to swelling and shrinking through moisture changes. Hamilton (1963) reported increased swelling potential with increasing plasticity index for Alberta soils (Figure 1). Therefore, soils with moderate plasticity to limit swelling but retain low permeabilities are desired. Eklund (1985) illustrated the zone of preferred plasticity (Figure 2).

Units such as the Paskapoo, Horseshoe Canyon, Belly River, and Wapiti Formations contain numerous beds of coal and sand or sandstone that could serve as conduits to transmit contaminants into the groundwater or surface water. For this reason, they are generally considered to be unsuitable for siting disposal sumps. In

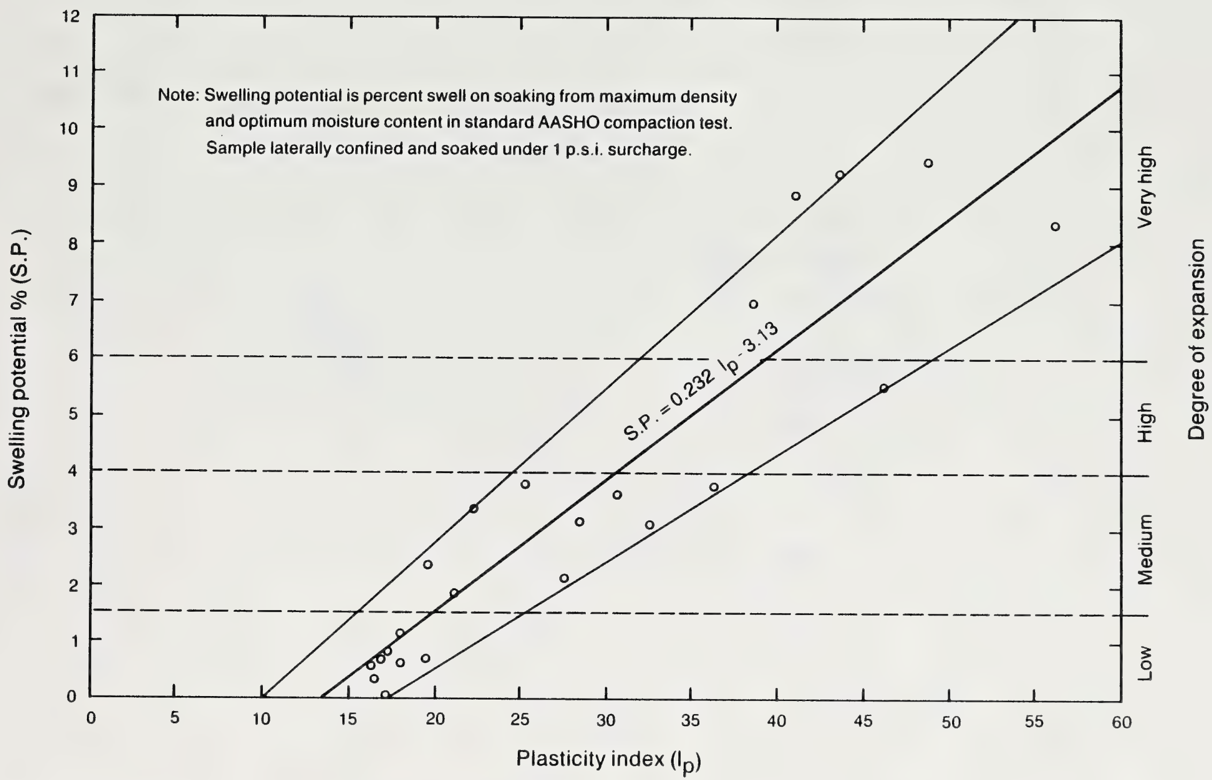


Figure 1. Classification chart for swelling potential - Alberta soils (from Hamilton, 1963).

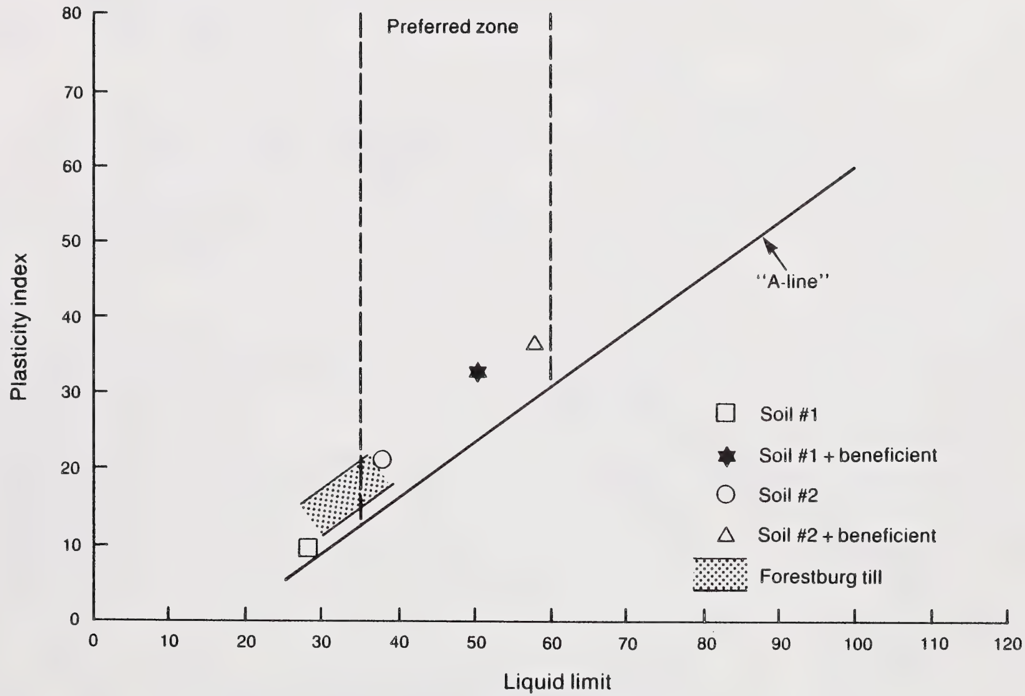


Figure 2. Preferred plasticity for soil liner materials (from Eklund, 1985).

general, material from the bedrock units is highly over-consolidated and does not have good compaction characteristics. Generally it is not adequate for construction of compacted liners.

The materials best suited for clay liners are the glacial tills that blanket most of the province. Till material generally has a high sand content which limits shrinkage, excellent compaction characteristics, and preferred plasticity (Figure 2). The only possible drawback is the significant proportion of smectitic clay minerals making up the clay fraction of the till. However, the most active clay species, sodic montmorillonite is not abundant, but rather calcic montmorillonite, chlorite, and illite make up the clay mineral species.

The grain size distribution of two tills, one found near Redwater, north of Edmonton, and the other from the Battle River area east of Red Deer, is shown in Figure 3. The materials have almost exactly the same average grain size distributions and the distributions for different samples at a site are very similar forming the tight band as illustrated. The compaction curves for the two tills are shown in Figure 4. Again the similarity is apparent. The steeply sloped compaction curves and the high maximum dry density achieved indicate a material with good compaction characteristics and a material with suitable characteristics for embankment construction. Table 1 lists the percentages of clay minerals in the clay size fraction for the two tills. The till in the more northerly section of Alberta contains a higher percentage of kaolinite. This is as expected from the geologic environment since the till in this area is closer to a source area containing dominantly kaolinitic bedrock than is the Battle River area. This slight difference in mineralogic species has little effect on the engineering properties of the two tills as shown by the plasticity of the two tills (Figure 5). The effect of brine on the Redwater till is shown to reduce the plasticity of the till (Figure 5). The same effect would be expected for the Battle River till.

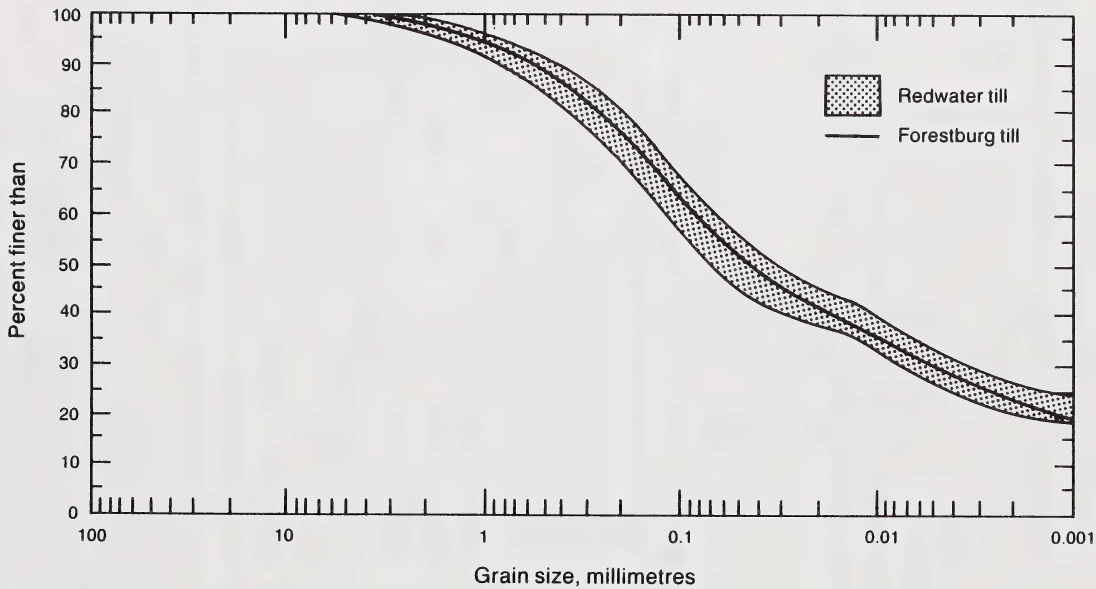


Figure 3. Grain size distribution of glacial till from Redwater and Forestburg, Alberta.

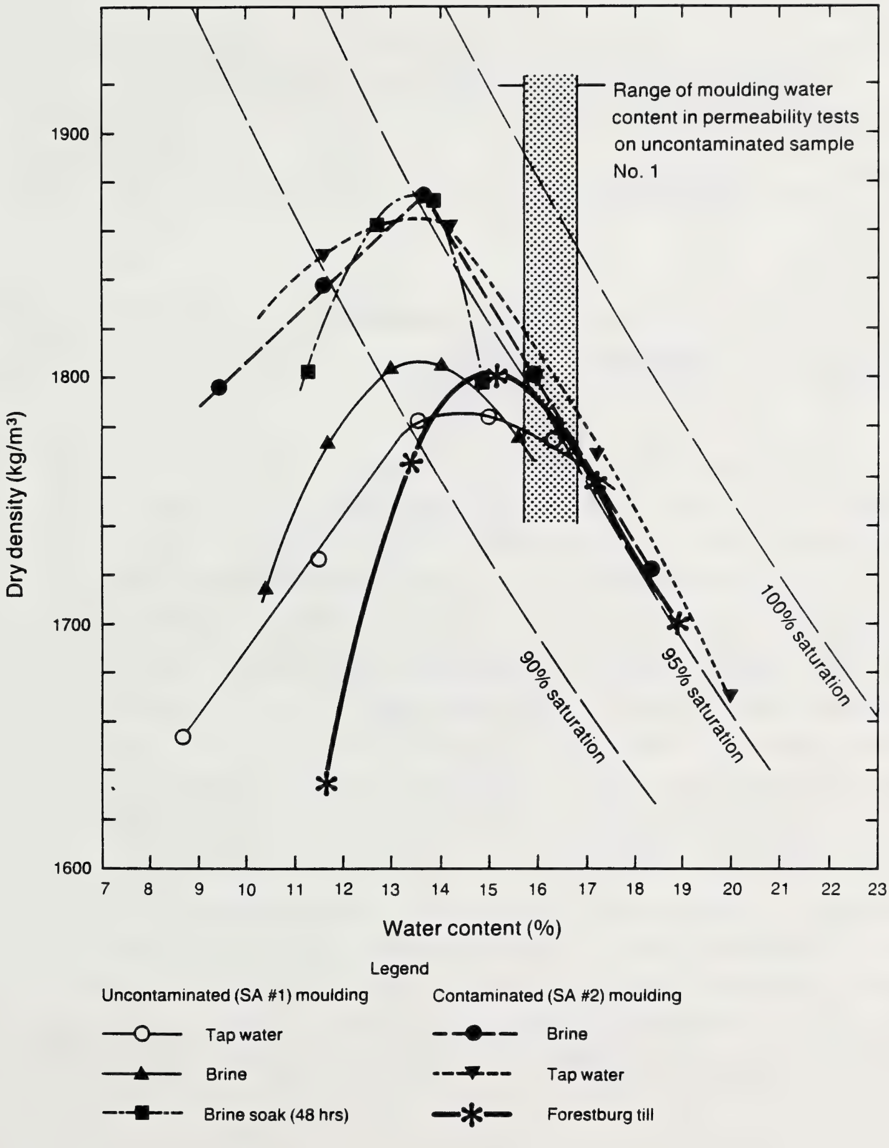


Figure 4. Compaction curves for glacial till from Redwater and Forestburg, Alberta (modified from Conlin and Claridge, 1986).

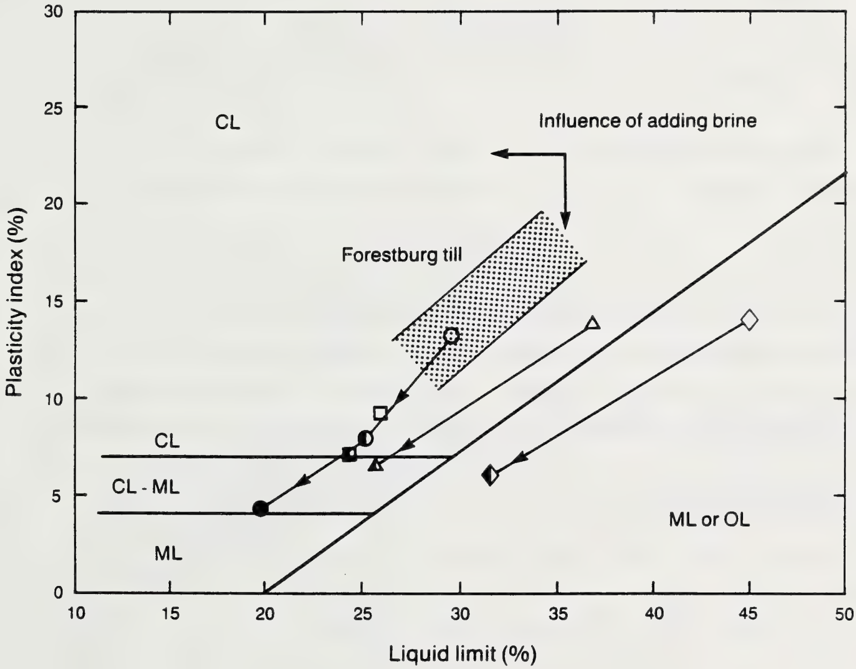
Table 1. Percentage of clay minerals in clay sized fraction.

PERCENTAGE OF CLAY MINERALS IN CLAY SIZED FRACTION				
Sample	Kaolinite	Illite	Chlorite	Smectite (Montmorillonite)
1*	20%	31%	7%	42%
2*	23%	36%	9%	32%
3**	7%	32%	7%	52%

* Glacial till from Redwater, Alberta.
** Glacial till from Forestburg, Alberta.

The similarity of the till materials from hundreds of kilometres difference in location suggest that till materials in these general areas will be suitable liner materials. Quality control in material selection will need to be exercised to maintain a minimum clay content of the till. A visual inspection and Atterberg limit tests may be adequate (Mundell and Bailey 1985). Where different types of materials are used, identification of particle size distribution, compaction, Atterberg limits, soil pH, and mineral composition should be done as suggested by Eklund (1985).

The similarity of till materials in portions of Alberta is conducive to extrapolation of test results in these general locations. A comprehensive study of the reaction between various drilling wastes and the till material and of the necessary quality control procedures needed for sump pit design would go a long way in providing containment facilities for the large volumes of drilling wastes throughout the province.



Legend

Sample No.	Type	Distilled H_2O	Brine (no soaking)	Brine soak (96 hours)
1	Uncontaminated	○	◐	●
2	Contaminated	△	▲	
3	Contaminated	□	◧	
4	Contaminated	◇	◆	

Figure 5. Plasticity of glacial till from Redwater and Forestburg, Alberta (modified from Conlin and Claridge, 1986).

6. LINER COMPACTION CHARACTERISTICS REQUIRED TO ACHIEVE OPTIMUM RETARDATION OF CONTAMINANT MIGRATION THROUGH THE LINER

The first step in considering liner properties is to examine the various methods of contaminant migration in earth materials.

The effectiveness of the liner to hold the waste for a predetermined length of time can be determined by assessing the hydraulic conductivity, diffusion rates, and attenuating capability of the liner material. For clay liners, the diffusion of certain chemicals along a concentration gradient can be of greater significance than advective transport of the chemicals by Darcy's Law along a hydraulic gradient. However, this occurs only where the hydraulic conductivity of the liner clay is very low. The hydraulic conductivity of both the primary and secondary porosity of the clay materials must be determined for safe design. Laboratory studies commonly measure only the primary hydraulic conductivity and therefore, underestimate K, commonly by an order of magnitude (Conlin and Claridge 1986). Clay materials are also known to react with many chemicals and to attenuate contaminant flow by holding some constituents within the clay fabric. This has been noted for dissolved organic carbon and heavy metals (Quigley and Rowe 1986). Attenuation of inorganic ions is less pronounced.

6.1 CONTAMINANT TRANSPORT BY DIFFUSION

At low hydraulic conductivity values the rate of transport of water and contaminants by advection becomes so slow that transport by diffusion is the dominant process. Quigley and Rowe (1986) have analysed the chemical profile under an existing domestic waste landfill and have found chloride and sodium ion migration to a depth of over 1 m where the hydraulic front had only advanced 3.6 cm. Figure 6 shows the profile of Na^+ and Cl^- concentrations below the clay-waste interface. Diffusion of the major ions and dissolved carbon occurred in response to the concentration gradient between the

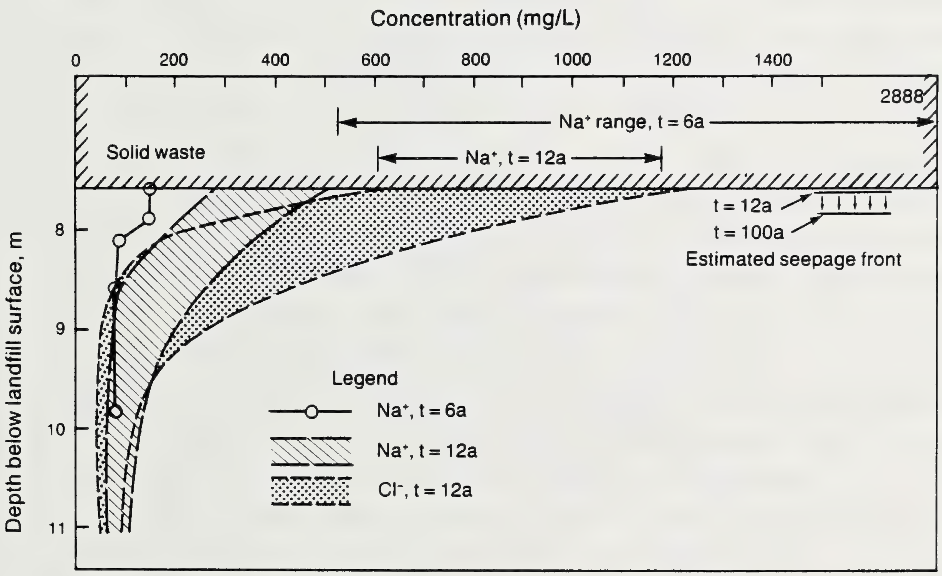


Figure 6. Pore fluid concentration of Na^+ and Cl^- (mg/L) in clay below waste leachate after 6 and 12 years of diffusion (from Quigley and Rowe, 1986).

permeant and pore water. The heavy metals, zinc, lead, copper, and iron were not diffused at the same rate, having migrated only 10 to 15 cm into the clay.

Rowe and Brooker (1985) have built a one-dimensional model of contaminant transport that includes a dispersion rate of 0.01 m^2/a, an advection velocity rate between 0 and 0.01 m/a and a range of absorption rates from geochemical reactions. The maximum concentration of dispersed permeant constituents is thus calculated for the bottom of the clay liner for various liner thicknesses and groundwater flow rates at the base of the liner. Figure 7 illustrates the maximum concentration of contaminant at the base of liner (c_b) versus the waste concentration (c_o), for various liner thicknesses (H), waste thicknesses (H_f) and for base velocities of 1 and 10 m/a assuming zero advective flow and no geochemical reactions. Figure 8 illustrates the effect of varying base velocities on the maximum base leachate concentration and the time required to reach this concentration for a one-metre thick liner and various heights of solid waste fill. The effect of sorption and advection velocity on the maximum leachate concentration at the base of the liner and the time for this concentration to be reached was also assessed.

The effect of the advective velocity on the maximum base concentration and time to reach maximum concentration is shown in Figure 9. Contaminant flow by advection begins to dominate flow by diffusion at as low a rate as 0.01 m/a. This velocity corresponds to a hydraulic conductivity of 3×10^{-8} cm/s and a gradient of unity. The permeabilities of Alberta tills are generally higher than this, suggesting that diffusion will not be a governing mechanism of contaminant transport.

The research performed by the Geotechnical Research Centre at the University of Western Ontario on the transport of contaminants by diffusion has suggested indirectly that further investigation of diffusion in Alberta materials is not necessary because the transport of contaminants by hydraulic flow will supersede diffusion. However, the modelling performed by this group demonstrates an effective

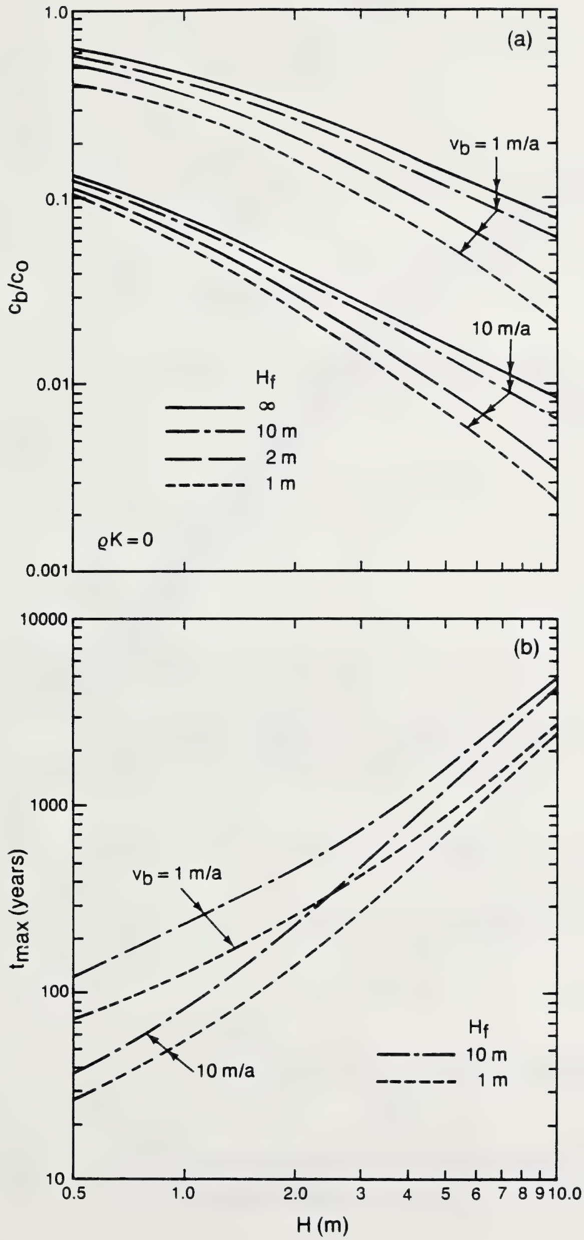


Figure 7. Effect of liner thickness upon (a) maximum base concentration and (b) time to reach maximum concentration (modified from Rowe and Brooker, 1985).

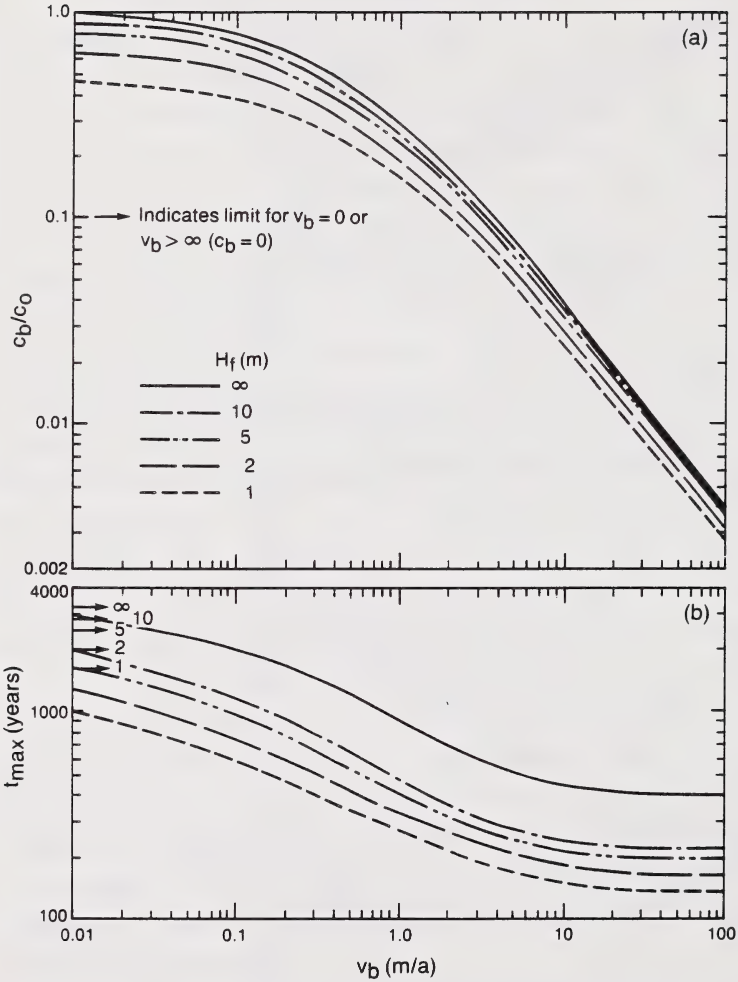


Figure 8. Effect of base velocity upon (a) maximum base concentration and (b) time to reach maximum concentration (from Rowe and Brooker, 1985).

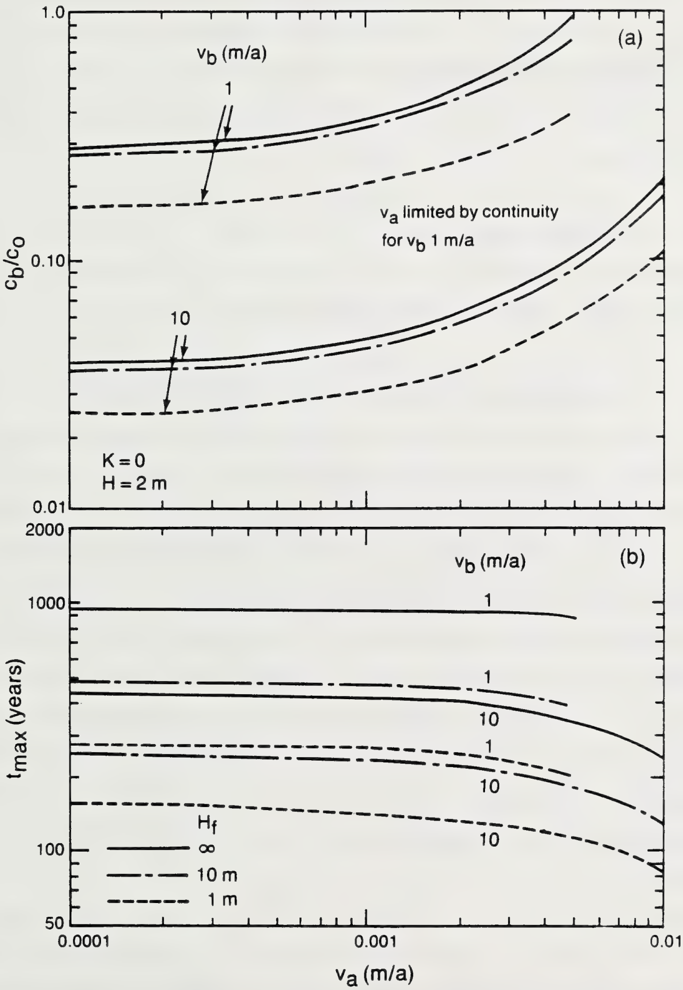


Figure 9. Effect of advection velocity upon (a) maximum base concentration and (b) time to reach maximum concentration (from Rowe and Brooker, 1985).

approach to determining leachate concentrations and the time to reach these concentrations for various conditions of waste volumes, liner thicknesses, seepage rates, adsorption rates, and groundwater flow rates.

6.2 TRANSPORT BY HYDRAULIC GRADIENT

The rate at which permeants seep or are driven through clay liners is governed by Darcy's Law:

$$q = k \times i \times A$$

where q is the rate of permeant advance

k is the hydraulic conductivity of the material

i is the hydraulic gradient or ratio between the thickness of the liner and the pressure head of the permeant

A is cross-sectional area

Increasing the thickness of the liner has a second order effect by reducing the gradient (i) and by lengthening the flow path between the waste and uncontaminated environment. However, the rate of flow can be retarded much more efficiently by designing a liner with a low hydraulic conductivity. A hydraulic conductivity of 1×10^{-7} cm/s is commonly required for liner materials. A one-metre thick liner with this hydraulic conductivity would hold a one-metre deep permeant for 30 years before any leakage would occur, and even then leakage would only occur at the rate of 3.6 cm of pore volume per year.

7. MEASUREMENT AND QUALITY CONTROL NECESSARY TO ASSURE THAT OPTIMUM HYDRAULIC CONDUCTIVITY CHARACTERISTICS ARE ACHIEVED

Construction of an effective liner requires a knowledge of the relationship between degree of compaction and hydraulic conductivity for the particular material being used. These data are obtained during laboratory testing of hydraulic conductivity and of compaction. Construction then requires a knowledge of the appropriate water content conditions at which to compact the material and the necessary amount of compactive effort to achieve the desired liner performance. Achieving this designed performance requires accurately measuring and controlling the density and water contents in the field to achieve the recommended values from laboratory tests.

7.1 LABORATORY TESTING OF HYDRAULIC CONDUCTIVITY

The review of literature assessing the various laboratory techniques of measuring hydraulic conductivity has shown that not only must the laboratory procedure accurately measure the permeability of the sample, but must also simulate the field conditions while the permeability is measured. Most testing procedures apply large gradients to the sample so that the test duration is dramatically decreased. This causes problems in that the sample is consolidated by the resulting high confining pressure and that dissolution of air occurs as the permeant flows through the sample causing unsaturated conditions. Both these conditions serve to lower the permeability of the sample. For these and other reasons the hydraulic conductivity measured in the field is commonly an order of magnitude higher than that measured in the laboratory. Every technique of measuring permeabilities has serious limitations, however, the constant flow procedure appears to be favorable because the test duration can be easily controlled, the sample can be molded into the compaction mold simulating the field compaction procedures, and the influent and effluent volumes and constituents can be easily monitored to perform analysis of the flow conditions in the sample during testing.

Researchers have measured the hydraulic conductivity of clays in the laboratory to values as low as 1 x 10^{-10} cm/s using various types of equipment (Acar et al. 1985a). Some of the common techniques for measuring the hydraulic conductivity of clays include the falling head test, the constant head tests applying large gradients (Lentz et al. 1985), the constant flow test (Quigley et al. 1985), and the consolidation test (Daniel et al. 1984). Both rigid wall and flexible-wall permeameters are used.

7.1.1 Rigid-Wall Permeameters

Rigid-wall permeameters have the advantage that the sample can be compacted directly into a compaction cell or an undisturbed sample in a shelby tube can be adapted directly into a permeameter (Daniel et al. 1984). The greatest fault of the rigid-wall permeameter is the occurrence of side wall leakage, especially if the soil is prone to shrinkage from permeant/clay interaction. Daniel et al. (1984), investigated side wall leakage by developing a double ring permeameter where the permeant flowing through the core of the sample would drain into a centre ring whereas the permeant flowing near the side of the sample would be collected by the outer ring. The permeabilities calculated by the volumes of flow into each ring were compared. They found that the increased permeability of shrinkage susceptible materials, as measured by the rigid-wall permeameter, is not accounted for by increased side effects. This suggests that the rigid-wall permeameter is modelling the condition of shrinkage of clays, yielding a decrease in confining stress and an increase in permeability, as would occur in both the laboratory and field settings. The rigid-wall permeameter in this case would thus more accurately describe the field permeability than a flexible-wall permeameter where the confining stress would be maintained. However, Edil and Erickson (1985) noted that rigid-wall permeameters were susceptible to channelling. It appears that if appropriate caution toward side effects and channelling is exercised, the rigid-wall

permeameter can be a simple and effective way of determining permeability.

7.1.2 Flexible-Wall Permeameters

A flexible-wall permeameter, commonly a triaxial cell, is better suited to test undisturbed samples and is more versatile in adjusting loading and pore pressures to model the field conditions. Carpenter and Stephenson (1986) tested the effect of gradient, backpressure, degree of saturation through monitoring B, and side effects and flow front by introducing a dyed permeant into a triaxial cell. They concluded that:

1. Sample diameter should be greater than 70 mm.
2. Length to width ratio should be 0.5 to 1.0.
3. Cut sample surfaces can reduce k by 5%.
4. Test duration should exceed 14 hours at gradients less than 200.
5. Backpressure is important to prevent piping.
6. Saturation of the sample can be determined by measuring B (response of pore pressure to increase in load).

They noted that the most common problems in determining hydraulic conductivity are system leaks, evaporation, dissolution of air in depressurized permeants, consolidation of samples caused by high (290) gradients, and channelling in rigid cells. The permeability values measured by the two types of cell were similar but no soils susceptible to shrinkage were tested. Daniel et al. (1984) also compared rigid and flexible-wall permeameters. They concluded that the type of permeameter used should be assessed for each project. The compaction-mold, rigid-wall cell more closely modelled compacted clays subject to low overburden pressures, whereas flexible-wall permeameters were more appropriate for modelling high overburden pressures.

7.1.3 Constant Flow Permeameters

A constant flow-rate permeability test described by Olsen (1966) and used by Fernandez and Quigley (1985) pushes permeant through a sample at a constant and measured rate. The pressure required to maintain the flow rate is measured and the gradient and hydraulic conductivity thus calculated. Some specialized equipment is needed to assure that no leakage occurs. The duration of testing is easily controlled using this apparatus and very low permeability values can be determined accurately. Both the permeant and the effluent volumes and characteristics are monitored. This allows evaluation of the degree to which the pore volumes were mobilized during testing. When different types of permeants are used sequentially, the composition of the effluent is examined with respect to the number of pore volumes passed through the sample. The presence of selected channels or cracks in the sample can be detected. If nearly one complete pore volume of flow occurs before the effluent reflects the change in composition of influent, the flow is occurring evenly through the matrix of the sample. If, however, the effluent quickly reflects the change in composition of influent at flow volumes significantly less than one pore volume, then flow is occurring through selected channels or cracks in the sample. This procedure is excellent for assessing the effects of permeant/clay interaction. The ability of the clay structure to attenuate certain influent constituents can also be assessed with this procedure (Quigley et al. 1985; Quigley and Fernandez 1987).

7.2 FIELD TESTING AND QUALITY CONTROL

Once the laboratory permeability to all anticipated permeants has been established, the liner must be built to the design specifications. In-situ testing of permeability is even more difficult than laboratory testing because of the duration needed for permeants to advance even a few millimetres and because of the spatial variability of the liner. Field determination of permeability is, therefore, not usually required.

7.2.1 Field Control

Field control of liner construction is exercised by carefully simulating laboratory conditions in the field. By monitoring the water content and compactive effort during construction, confidence of liner uniformity can be established. Samples of the completed liner can also be tested in the laboratory for confirmation of permeability. Monitoring the compaction density and water content during construction and randomly testing for permeability will establish confidence limits for liner performance. Regulation should take a statistical form in which rather than requiring a specific value for permeability, water content and compaction density, a confidence interval for each is specified (Harrop-Williams 1985).

7.2.2 Field Testing of Hydraulic Conductivity

Where field permeability tests are required, several researchers have investigated techniques for field testing. Day and Daniel (1985) discuss the advantages of using a single ring infiltrometer and present a case history where it was used. They suggest further experience is needed before this technique would be recommended. It would be difficult to measure hydraulic conductivities of less than 1×10^{-7} cm/s using this technique. Another technique using piezometers was used by Jones (1985). He placed pipes into the liner with a ship's auger, bailed them out, and monitored the fluid level recovery. Keller et al. (1985) measured the permeability of unweathered Saskatchewan till using carefully installed piezometers. The field measurements of permeability (5×10^{-7} cm/s) were two orders of magnitude higher than the laboratory measurement of the till matrix. They attribute the high permeabilities to a fracture network probably induced by postglacial rebound.

Laboratory tests of hydraulic conductivity have also been compared to field conductivities determined through pond stage monitoring. However, this is not an option for field testing since

the liner would already be in place and the contaminants in the sump. However, even this technique of measuring field permeabilities is difficult with open ponds subjected to evaporation losses.

7.2.3 Compaction Considerations

Many researchers have investigated the relationship between compaction and permeability. Mundell and Bailey (1985) discuss the compaction theory as it relates to permeability at length but conclude little more than is already well-known; clay should be compacted above 95% standard compaction density at a water content slightly above optimum. They recommend compacting the soil to a water content and dry density as indicated by the shaded control areas in Figure 10. Eklund (1985) concluded from his investigation on the performance of soil liners that material classification can be confidently limited to particle size distribution, compaction, Atterberg limits, soil pH, and mineral composition.

Kleppe and Olson (1985) investigated the relation between clay shrinkage from desiccation, compaction water content, and percent sand. Shrinkage increased with increasing compaction water content and with decreasing sand content as illustrated in Figure 11. However, permeability decreased with increasing compaction water content and with decreasing sand content as illustrated in Figure 12. A balance between these parameters was found with 75% sand to limit shrinkage and compacting slightly wet of optimum to maintain a permeability of 10^{-7} cm/s.

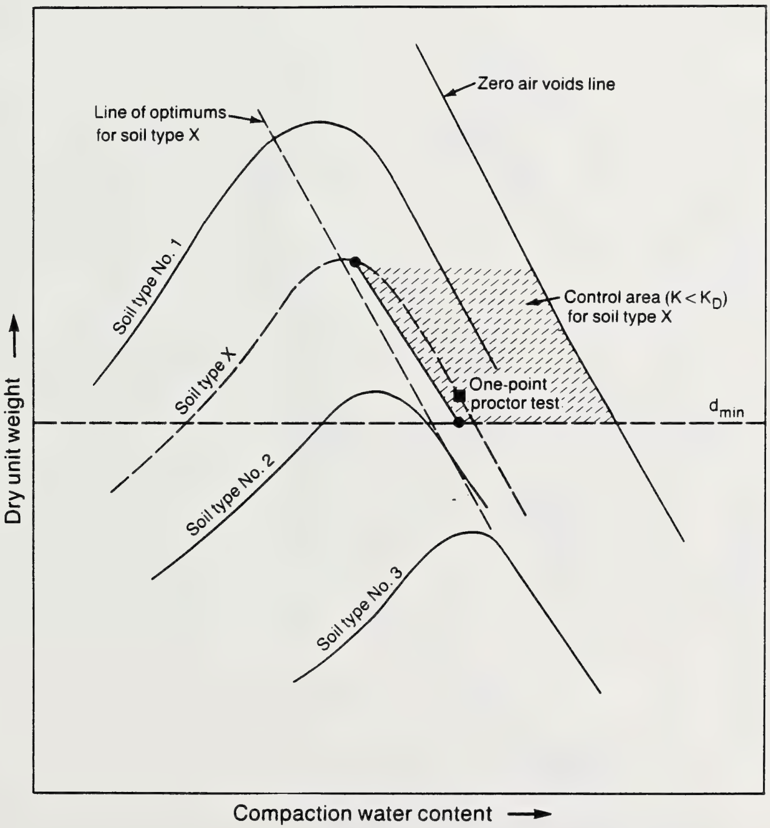


Figure 10. Field control area for compaction water content (from Mundell and Bailey, 1985).

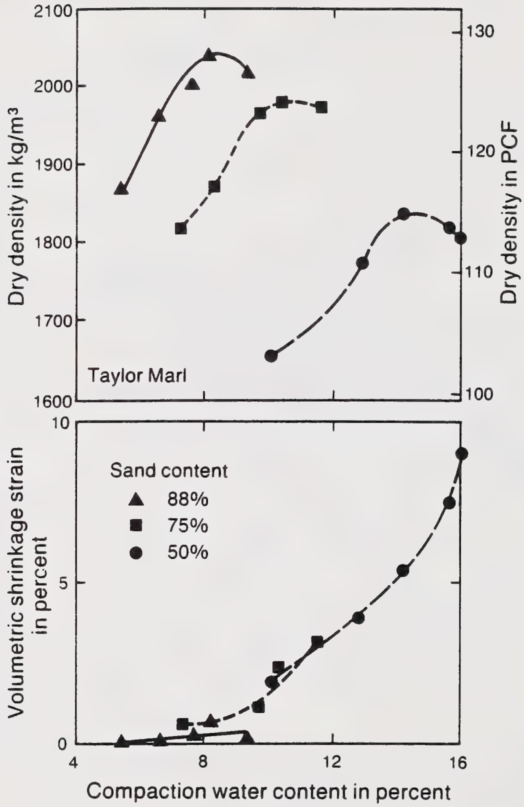


Figure 11. Moisture-density relations and shrinkage strains for specimens of Taylor Marl mixed with various percentages of sand (from Kleppe and Olson, 1985).

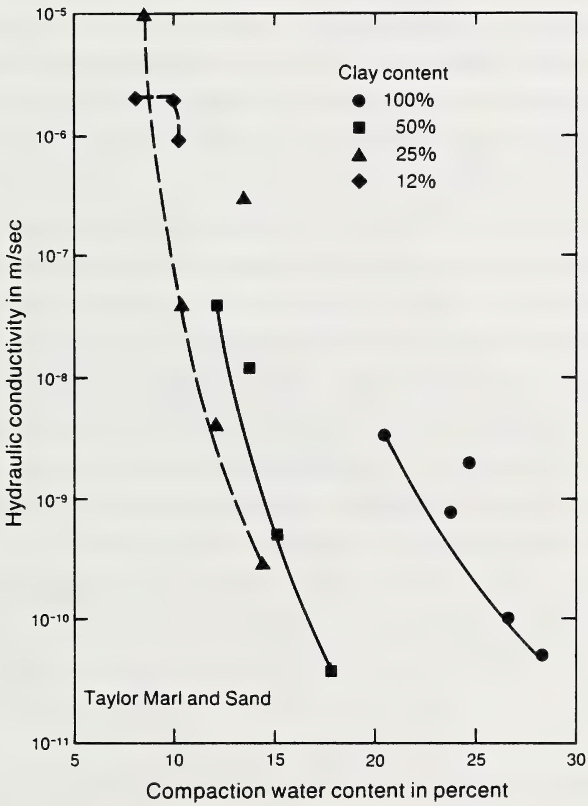


Figure 12. Hydraulic conductivity for various mixtures of Taylor Marl and sand compacted at various water contents (from Kleppe and Olson, 1985).

8. COMPOSITION AND NATURE OF DRILLING WASTES

The composition of the waste materials varies with the type of materials that are penetrated during drilling, the type of drilling muds used, and the operational procedures. A wide variety of liquid and solid wastes including hypersaline solutions, organic compounds, heavy metals, hydrocarbons, acidic and caustic solutions, and general refuse may be encountered in a given well site sump. The performance of the liner materials will be affected by the interaction of the waste constituents with a synthetic or clay liner. Therefore, the characterization of waste materials must be an integral part of the pit design process.

Initial analysis of the drilling wastes associated with KCl and NaCl mud systems indicates that the contaminants from both the liquid and solid phases of waste are predominantly hypersaline solutions (Macyk et al. 1987). The KCl-type mud wastes contain as much as 25 000 mg/L of K in the waste water. Commonly 1 to 2% of the liquid phase is oil, however, the specific type of oil and other organic compounds is not known. The pH of the waste water is typically 8.2 for all muds but reaches values as high as 11.9 for some samples with corresponding alkalinity of approximately 1000 mg/L. The hypersaline NaCl and KCl solutions seem to be the major concern for the liner/permeant reactions.

9. ATTENUATION CHARACTERISTICS OF NATURAL LINER MATERIALS

Researchers investigating hydraulic conductivity of clays to various permeants have noted varying rates of flow of physically similar permeants but with differing chemical constituents. Rowe and Brooker (1985) use a dimensionless quantity ρk between 0 to 100 to describe the sorption due to geochemical reaction. They note that sorption may be particularly important for heavy metals and NH_4. Quigley and Rowe (1986) note that different constituents of the same waste leachate migrated into a clay liner at differing rates. Na^+ and Cl^- diffused up to 1.1 m into the clay while Cu, Fe, Pb, Zn, and dissolved organic carbon were more strongly attenuated. Quigley and Fernandez (1987) note that K^+ was strongly attenuated by Southern Ontario brown soils. Grim (1968) also discusses the attenuation of K^+ by smectitic clay structure.

A more in-depth study of attenuation was performed by Eklund (1985). He prepared two column tests, one filled with solid waste and another filled with solid waste with a layer of clayey soil underlaying it. The concentration of contaminants from the waste and waste/soil columns are shown in Figure 13. The total organic carbon, total dissolved solids (conductivity), sodium and barium were attenuated, but the sulphur was not.

Park (1986) performed a literature review on the evaluation of permeable materials for removing pollutants from leachate. The following paragraphs are excerpted from his review:

> *"Griffin et al. found that of the three basic types of clay minerals, montmorillonite retained metals better than illite or kaolinite. For the metals tested, those that were considered to be highly attenuated were: Pb, Zn, Cd, and Hg. Precipitation was believed to be the mechanism. Those showing moderate attenuation were: Fe, Si, K, NH_4, and Mg, possibly attributable to ion exchange; Na and Cl showed little attenuation, while Ca, Mn, and B were not retained at all."*

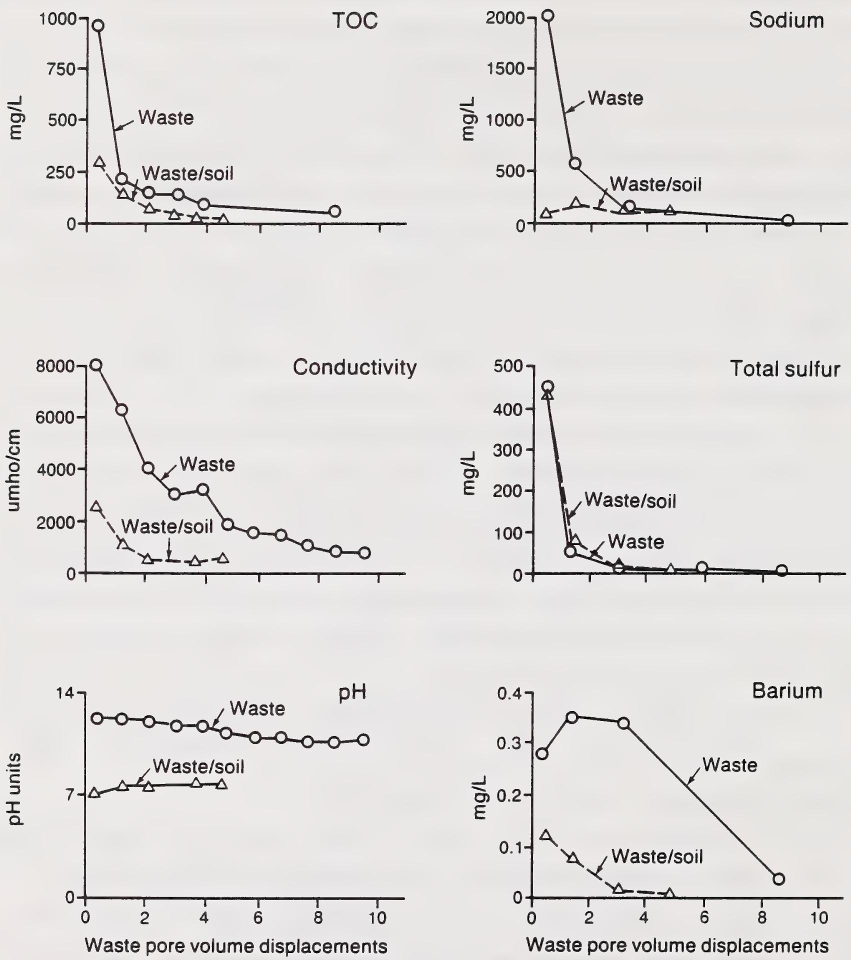


Figure 13. Leachate/soil interactions (concentration vs. waste pore volume displacement) (from Eklund, 1985).

"The interactions of inorganics and soils as described by Fuller et al., may be summarized:

> *The amount of clay in a soil may be the most useful indicator of its ability to sorb inorganics, especially cations.*
>
> *Cations are removed from solution by precipitation or ion exchange on the clay mineral surface.*
>
> *Anions such as As, Se, C, and CN will be mobile in alkaline soils. They can be sorbed in anion exchange reactions or by the hydrous oxides of Fe, Mn or Al, which are present in most soils."*

10. CHEMICAL AND PHYSICAL CHANGES IN LINER PERFORMANCE CAUSED BY INTERACTIONS WITH CONTAMINANTS

Many factors may contribute to the deterioration of liner performance, not the least of which is waste/liner interaction, which can alter the hydrophysical properties of the liner clay fabric. The physical and chemical properties such as density, viscosity, dielectric constant, octanol/water partition coefficient, solubility and concentration of various constituents in the waste leachate affect both the dynamics of fluid flow described by Darcy's Law, and the electrochemistry and pore size and distribution of the clay medium which determines the intrinsic permeability of the liner.

10.1 EFFECTS OF PHYSICAL PROPERTIES OF PERMEANTS

As described previously, Darcy's Law determines the rate at which fluid will flow through a certain medium under a known pressure head. The permeability (hydraulic conductivity) k in the equation is dependent on fluid properties as described in the equation below:

$$k = k \frac{\rho}{\mu} g$$

where k = intrinsic permeability
ρ = fluid density
μ = fluid viscosity
g = gravity

The permeability of a permeant will vary proportionally with fluid density and inversely with fluid viscosity.

10.2 EFFECT OF CHEMICAL PROPERTIES OF FLUIDS

Waste fluid chemistry can influence permeability, apart from altering the clay fabric, by its hydrophobicity or solubility in water, and by precipitation of certain chemicals or growth of microorganisms in pores. Changes in concentration of certain ions can lead to precipitation of gypsum ($CaSO_4 \cdot 2H_2O$) or jarosite

$[KFe_4(SO_4)_2(OH)_6]$ (US EPA Report 1986). The physical presence of microorganisms as well as gases emitted from chemical reactions can cause clogging of pores decreasing permeability.

10.3 HYDROPHYSICAL CHANGES IN SOIL FABRIC FROM REACTIONS WITH ORGANIC AND INORGANIC PERMEANTS

10.3.1 Diffuse Double Layer Theory

The behaviour of clays is dynamic because of the large surface area of the platelike particles and the electronegativity of the surface of the clay particles. Mitchell (1976, pp. 112-113) described the chemical and physical environment around clay particles in the following excerpt as the Diffuse Double Layer.

> *"In a dry clay, adsorbed cations are tightly held by the negatively charged clay surfaces. Cations in excess of those needed to neutralize the electronegativity of the clay particles and their associated anions are present as salt precipitates. When the clay is placed in water the precipitated salts go into solution. Because the adsorbed cations are responsible for a much higher concentration near the surfaces of particles, there is a tendency for them to diffuse away in order to equalize concentrations throughout. Their freedom to do so however, is restricted by the negative electric field originating in the particle surfaces ...The negative surface and distributed charge in the adjacent phase are together termed the DIFFUSE DOUBLE LAYER ..."*

The double layer thickness is affected by both organic and inorganic substances. Acar et al. (1985b) discusses these effects with the use of the following equation:

$$H = f[(\frac{DT}{ho^2 v^2})^n]$$

where H = double layer thickness

D = dielectric constant

T = temperature

ho = electrolyte concentration

v = cation valence

n = some constant ($\simeq 1/2$)

The dielectric constant, temperature, electrolyte concentration, ionic valence, size of hydrated ions, pH and anion adsorption all affect the double layer thickness (Lambe 1958).

The double layer thickness is proportional approximately to the square root of the dielectric constant. This is important for organic permeants, which have very low dielectric constants (3 to 10 compared to 80 for water). Thus organic permeant will tend to decrease the double layer thickness causing desiccation of the clay and an increase in permeability.

10.4 EFFECT OF SALINE SOLUTIONS

The electrolyte concentration is important for inorganic saline permeants such as are encountered in drilling wastes. The double layer thickness is inversely proportional to the concentration of electrolyte and to the valence of its constituent. Anderson and Brown (1981) describes the effect of salt on the behaviour of clays as follows:

> "*As salt concentration in interparticle spaces increases, the cationic cloud is compressed closer to the clay surface, resulting in a decrease in electrostatic repulsion and interlayer spacing. Weiss (1958) noted the direct relationship between salt concentration and interparticle spacing in smectitic clay minerals in a study using distilled water and several concentrations of sodium chloride in water. Both distilled water and 0.01 N NaCl gave infinite interlayer spacing values (the clay was completely dispersed), while 1.0, 3.0, and 5.0 N NaCl gave interlayer spacings of 0.93, 0.61, and 0.58 nm,*

respectively."

Alther et al. (1985) studied the influence of inorganic permeants on the permeability of bentonite. They observed that bentonite clay displayed the greatest amount of shrinkage and resulting increase in permeability when exposed to divalent cation salts such as Ca^{++} and Mg^{++} but a saturation limit of these salts is reached so that above this concentration, the salt has no greater effect. They found that the K^+ cation and Cl^- anion had a greater effect of increasing flocculation and permeability than did the Na^+ and $CO_3^=$ anion. A simple test involving soaking the bentonite material under increasing concentrations of KCl solution was used to assess the effect of K^+ concentration on shrinkage of the bentonite clay.

They explained the effect of inorganic solutions on the bentonite clay with the Gouy-Chapman diffuse double layer theory. Shrinkage and subsequent cracking of bentonite increased with the concentration of the electrolyte concentration containing the K^+ ion. A dramatic increase in flocculation (decreased double layer thickness) of bentonite clay with KCl concentrations increasing from 3 to 10% was noted.

10.5 EFFECT OF ORGANIC SUBSTANCES

A report written by the Research Triangle Institute for the Environmental Protection Agency (1986) described the interaction of organics with clay as follows:

> *"As the dielectric constant decreases, the fluid film surrounding the clay that contains positive cations must be thinner for the negative surface charge on the clay to be neutralized. For a constant surface charge, the surface potential function will increase as the dielectric constant decreases. Since most organic liquids have dielectric constants substantially lower than water, it is to be expected that the double-layer thickness would be reduced (with an associated tendency toward flocculation) when an*

organic liquid rather than water surrounds the clay particle. Due to the effects of dielectric constant on the electrical double layer, there is a relationship between the dielectric constant of an adsorbed fluid and interlayer spacing exhibited by clay particles. In general, interlayer spacing decreases with a decrease in the dielectric constant, although this apparent relationship can be complicated by the other factors that affect interlayer spacing."

As mentioned above, the diffuse double layer theory does not provide a simple explanation of permeant/soil interaction in many cases. For example, the permeability of a kaolinite clay will decrease with low concentration organics such as benzene (Acar et al. 1985a) whereas the permeability of bentonitic clays will increase dramatically with similar organics such as xylene (Anderson et al. 1985). Conlin and Claridge (1986) noted how a smectitic clay flocculated, increasing permeability with an NaCl solution greater than 0.5 N concentration whereas the same material dispersed, reducing permeability for a less concentrated solution.

A United States Department of Energy (1985) literature review noted conflicting results from studies involving the effects of organic solvents on swelling and hydraulic conductivity of clays. Table 2 summarizes some of the research findings. The same substances appear to have caused both shrinkage and swelling, and caused both increased and decreased hydraulic conductivity.

Another example of conflicts in the literature involved the effect of permeants of various dielectric constants on the permeability of clay. Acar et al. (1985a) noted that increasing free swell (therefore, decreasing permeability) results with increasing dielectric constant, as seen in Figure 14. Green et al. (1981) reported the opposite to be true and measured an increasing permeability with an increasing dielectric constant. Green further tested his materials and also noted increasing free swell with

Table 2. Effects of organic solvents on swelling/hydraulic conductivity of clays.

A. Swelling of Clays (Relative to Effect of Water)		
1.	Shrinkage	- hexane, benzene, acetone, butanol, glycerol (Barshad 1952)
		- >80% acetone, propanol, ethanol, 1,5-pentanediol, ethylene glycol (Brindley et al. 1969)
		- dioxane (Brindley et al. 1969)
B. Hydraulic Conductivity (Relative to Water)		
1.	Increased	- heptane, xylene, acetone, methanol, ethylene glycol, aniline, acetic acid (Anderson and Brown 1981)
		- kerosene, diesel fuel, gasoline, motor oil (Brown and Thomas 1984)
2.	Decreased	- benzene, xylene, carbon tetrachloride, trichloroethylene, acetone, methanol, glycerol (Green et al. 1981)
		- benzene, phenol, nitrobenzene (Acar et al. 1984)
		- 0.1% organics (slight decrease) (Acar et al. 1984)
3.	No Effect	- <1% organics (Ely et al. 1983)

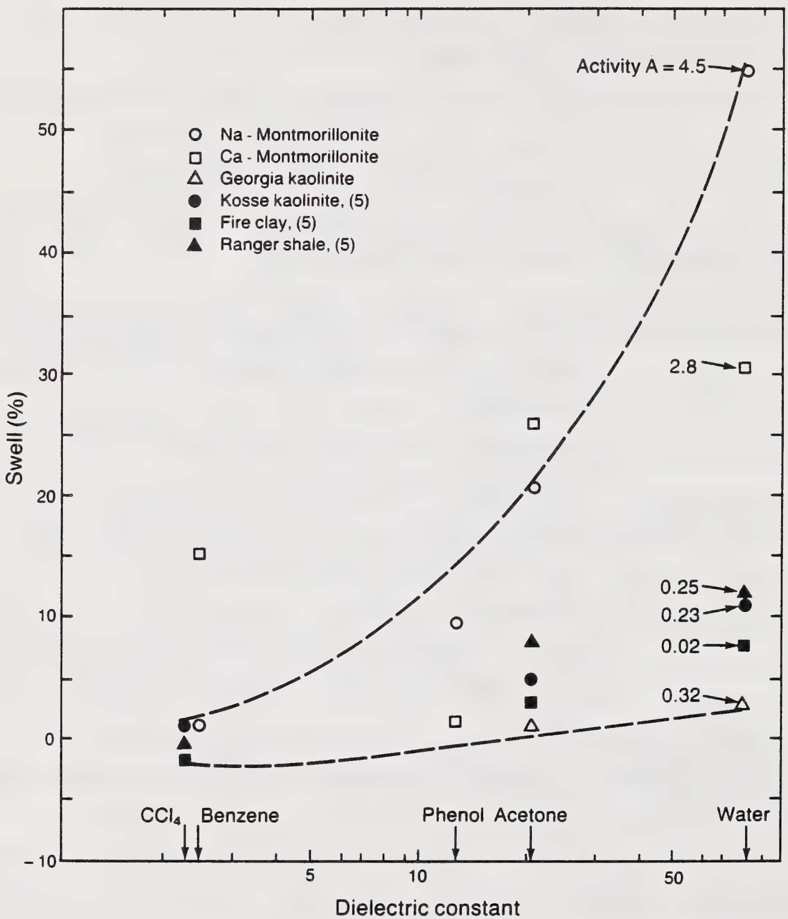


Figure 14. The effect of organic fluids on the swelling behavior of compacted soils (from Acar et al, 1985a)

increasing dielectric constant; an apparent contradiction with his permeability measurements. He thus explained the conflict by analysing the movement of permeants through the soil medium. Hydrophobic substances, such as, benzene, xylene, and carbon tetrachloride are more strngly sorbed by soil particles and thus move more slowly through the medium. Quigley et al. (1985) also noted the surprisingly low permeability of clay to benzene. Through analysis of effluent fluids the low permeability of benzene was attributed to its low solubility with water; the benzene could not enter the pore space initially filled with water. When more soluble ethanol replaced the pore fluid and then benzene, which is soluble in ethanol, the permeability went from 1×10^{-8} to 5×10^{-8} to 5×10^{-5} cm/s for water, ethanol and benzene respectively. Anderson et al. (1985) also noted large permeability increases when calcareous smectitic clay soil mixed with 9% bentonite was permeated by methanol and xylene. Permeability typically increased from 5×10^{-8} to 1×10^{-5} cm/s. The full effect of the change in permeability was not noted until more than one pore volume of influent was introduced.

10.6 CASE STUDIES

Komex Consultants Limited prepared a study of the effects of brine on a compacted clay liner. Their study involved a laboratory testing program using Alberta till liner materials from the Procor Limited Brine Pond and hypersaline NaCl solutions. They also reviewed case studies that used similar materials. Case studies were performed at the Imperial Oil Limited Brine Pond and the Chevron Brine Pond both at Redwater, Alberta, the Dome Brine Pond at Fort Saskatchewan, Alberta, and of Saskatchewan glacial till.

Conlin and Claridge (1986) performed an extensive laboratory test program studying the effects of hypersaline NaCl brine on the permeability of Alberta glacial till clays used for constructing the liner of the Procor Brine Pond near Redwater, Alberta. Their major conclusions from the testing program were that:

1. The saturation of the laboratory sample has a significant effect on permeability measurement.
2. Introducing brine to a fresh water compacted sample causes an increase of permeability of about one order of magnitude.
3. Brine contaminated undisturbed samples of the clay liner have permeabilities to brine approximately one order of magnitude higher than recompacted, brine contaminated samples.
4. The effect of brine on clays occurs rapidly.

Ten laboratory tests in all were conducted on the materials. Differences of clay content, compaction density, and saturation masked many of the factors causing differences of permeabilities due to fresh or brine permeants as these factors are considered to be small.

The effects of brine permeants on increasing the permeabilities as measured in the laboratory, did not explain the high permeabilities measured in the field, therefore, Conlin concludes that liner protection from physical deterioration is most important. Compacting the liner material with brine as the molding liquid will lower the permeability a little, but he notes that it may reduce the potential for shrinkage caused by brine permeants.

This study on the effects of brine on compacted glacial till liners in Alberta noted a one order of magnitude increase in permeability of the liner caused by the saline permeant. A more complete breakdown of his findings is somewhat more interesting. Conlin noted the following permeabilities from the associated conditions outlined in Table 3.

The permeability of the liner measured in the field was three orders of magnitude less than the permeability measured using a standard permeability test with a compacted sample and a freshwater permeant. The laboratory tests suggest that only one order of magnitude is directly attributable to the change from freshwater used in the laboratory tests to brines. The brine appears to have

Table 3. Permeabilities of glacial till under various laboratory and field conditions with fresh and brine permeants.

Sample Type	Permeant	Permeability
Recompacted	fresh	3×10^{-9}
Recompacted with brine	brine	3×10^{-9}
Recompacted	brine	3×10^{-8}
Undisturbed	brine	2×10^{-7}
Field	brine	2.5×10^{-5}

affected the liner to a greater degree than was accounted for using the testing procedure employed. Similar high field permeabilities have been encountered in case studies cited by Conlin and Claridge (1986) and by Jones (1985), who observed permeabilities much higher than anticipated from the laboratory tests.

EBA Engineering Consultants Limited investigated the cause of pond leakage at the Imperial Oil Limited pond near Redwater. They found that the field permeability (2.1 to 3.0×10^{-6} cm/s) was significantly higher than the permeabilities measured in the laboratory (typically 5×10^{-8} cm/s). They attributed this difference to differential settlement of the pond, dessication of pond sideslopes, and to chemical shrinkage of clay till. Likewise permeability of till materials to be used for a liner of the Dome Brine Pond increased between 20 and 63 times when permeated with brine permeants. A similar laboratory procedure performed on till from Saskatchewan, which compared closely to the materials near Redwater, Alberta, indicated increased permeability of fivefold for brine permeants (Conlin and Claridge 1986).

The case studies reviewed above have all used glacial till materials native to Alberta, but only the effect of a NaCl brine solution was investigated. A highly saline KCl solution is expected to have a greater effect on clays with smectitic minerals, as suggested earlier by Alther et al. (1985). The effects of organic

permeants on the smectitic tills of Alberta may be even more pronounced, increasing permeabilities by several orders of magnitude. The effects of these permeants on Alberta tills need to be assessed.

Laboratory studies of the effects of permeants on the hydraulic conductivity of clays have generally not been able to account for the full discrepancy between laboratory and field measurements of permeability. An experimental procedure needs to be developed that can confidently predict the full effect of various permeants as well as the effects of field conditions and quality control during construction or any other factors causing this discrepancy. The effect of scale between the laboratory and the field may have much to do with this discrepancy. A small amount of sample shrinkage may only cause very small fractures in the laboratory but the same amount of shrinkage in the field may cause considerably larger cracks. A scientific approach considering all of the contributing qualities of both permeants and clay structure is recommended over site specific studies.

11. CONCLUSIONS

1. The glacial till materials found throughout most of Alberta have remarkably similar engineering and mineralogic properties and are generally suitable for liner construction materials.
2. Increasing the sand content of liner clays will decrease shrinkage from dessication but increase permeability. Decreasing the compaction water content of liner clays will likewise decrease shrinkage but increase permeability. An optimum combination appears to be a maximum sand content of 75% to limit shrinkage while compacting at slightly above optimum water content to keep the permeability below 1×10^{-7} cm/s.
3. Diffusion can be the major mechanism of contaminant transport where advection is below 1×10^{-8} cm/s. However, advective flow is generally greater than this for the clay materials considered for liners in Alberta, therefore, diffusion will rarely be the governing mechanism. An effort in modelling as demonstrated by Rowe and Brooker (1985) applied to advective contaminant transport would be useful for predicting maximum contaminant concentrations and the time to reach these concentrations for various combinations of liner permeability, waste volume, attenuation characteristics, and groundwater conditions.
4. The type of permeameter to be used for determining the hydraulic conductivity must be assessed according to the field conditions to be simulated. Rigid-wall permeameters more accurately simulate the condition of slight shrinkage of clay liners from osmotic dessication or reduction in double layer thickness due to permeant/clay interaction. Flexible-wall permeameters can simulate conditions of high

overburden pressures, test undisturbed samples and can assess the degree of saturation of the sample which is critical for permeability measurement.

5. A constant flow-type permeameter appears to be the best method of testing apparatus because the duration of the test is easily controlled and the volumes and chemical constituents of the influent and effluent can be easily monitored.
6. Field permeabilities are often much higher than those measured in the laboratory. The reasons for this are not well understood, however, a combination of poor quality control of liner construction, operating procedures causing desiccation, differential settlement, and frost action in the liner have been cited as reasons by various authors. Laboratory tests may also show unrepresentatively low permeabilities because of unsaturated conditions.
7. Smectitic clays are sensitive to an increase in permeability from hypersaline and organic permeants because the double layer thickness is reduced as less polar or ionic permeants replace water in the clay structure. Osmotic dessication, caused purely by the concentration gradient of ionic species between the permeant and interstitial fluid, can result in clay shrinkage, and thus, increase permeability through increased secondary porosity.
8. Laboratory studies of smectitic clay subjected to solution with high concentrations of K^+ have demonstrated severe shrinkage.
9. Case studies of performance of glacial till liner for storing drilling muds have concentrated on NaCl type wastes. Studies involving KCl type muds with the range of clays that may be used for liners have not been performed.

10. Permeants with low dielectric constants, for example, organic fluids such as benzene, xylene, and CCl_4 will reduce the double-layer thickness of clays and cause shrinkage, but may indicate very low permeability in the laboratory because of their hydrophobic behaviour and insolubility, thus not being able to penetrate the water filled pores.
11. Attenuation of various leachate constituents, such as, sodium, potassium, total dissolved solids, total organic carbon, and heavy metals have been observed. Quantifying this attenuation capability is difficult, but it generally increases with increasing cation exchange capacity of the clay.
12. The interaction between contaminants and clay liner materials is not straightforward, therefore, classification of liner clay materials and waste constituents must precede liner design.

12. RECOMMENDATIONS

1. A scientific study should be conducted to investigate the chemical and structural factors in construction and performance of clay liners composed of Alberta till. The study should further evaluate the effects of interactions of the various chemical constituents of drilling wastes with the liner material on the long-term permeability of the clay liners. The study should:
   a) involve the use of a constant-flow permeability-testing apparatus along with careful evaluation of influent and effluent volumes and composition;
   b) concentrate on accounting for the discrepancy between field and laboratory measurements of hydraulic conductivity; and
   c) explore the potential methods for treatment of the clay material to enhance compaction characteristics, reduce permeability, and decrease potential for shrinkage, both from chemical and physical desiccation.
2. An expert system should be developed to access the extensive body of knowledge on the interactions between different types of clay liners and specific permeants to allow prediction of the behaviour of a particular clay with a particular suite of drilling-waste constituents. Such a system would allow assessment of environmental sensitivity of a proposed sump site, optimum liner design, and assignment of quality control during construction.
3. Guidelines for construction of clay liners for drilling-waste disposal sumps should specify acceptable confidence limits within which parameters such as compaction water content, dry density,

material variability, and hydraulic conductivity are allowed to vary, rather than identifying specific values for these parameters.

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14. GLOSSARY

advection - The process by which solutes are transported by the bulk motion of the flowing groundwater.

Atterberg limits - Refer to the moisture conditions of liquid limit, plastic limit, plasticity index, and shrinkage limit.

capillary action (capillarity) - The rise or movement of fluid in the interstices of a soil due to capillary forces.

chemical flux - Rate of flow of a chemical species expressed as mass per unit cross-sectional area per unit time. The chemical flux may be obtained by multiplying total volumetric flux by chemical concentration.

Darcian velocity - Velocity of aqueous phase based on total cross-sectional area obtained by dividing volumetric flow rate by cross-sectional area. The actual velocity of water in the soil is obtained by dividing the Darcian velocity by soil porosity.

degree of saturation (%) - Percent of the void volume in soil that is filled by water. Same as moisture content expressed in terms of percent.

expert system - An expert system is a computer program that is designed to assist a user in solving problems.

flux - Flow rate per unit area.

influent - Flowing in.

leachate - This term is used to emphasize the chemical species in an aqueous medium. Leachate may have several chemical species in varying concentrations in an aqueous medium. Leachate may also be generated by organic solvents.

liquid limit - The liquid limit is the moisture content at which a soil passes from a plastic to a liquid state.

moisture content (% v/v) - Percentage of soil volume occupied by moisture.

permeant - A substance that passes through the substance or mass of; penetrates through the pores or interstices of.

plastic limit - The plastic limit of soils is the moisture content at which a soil changes from a semisolid to a plastic state.

plasticity index - The plasticity index is defined as the numerical difference between liquid limit and plastic limit.

porosity - The ratio of volume of voids in a soil mass to the total volume of the mass.

pressure head - Expressed in head of water. Water pressure head defined relative to atmospheric pressure is given by:

$$\Psi = \frac{(P_w - P_a)}{p_w g}$$

where
P_w = water pressure
P_a = pressure in air phase taken as atmospheric pressure
p_w = sensity of water
g = gravitational acceleration.

primary porosity - Is due to the soil or rock matrix.

relative hydraulic conductivity - The ratio of hydraulic conductivity of a given soil at a certain moisture content with the hydraulic conductivity of the same soil in saturated condition.

saturated hydraulic conductivity - Hydraulic conductivity of a saturated soil with respect to water.

saturated medium - A porous medium in which all voids are filled with fluid under pressure greater than atmospheric pressure.

secondary porosity - May be due to such phenomena as secondary solution or structurally controlled regional fracturing.

seepage - Movement of water (vertically downward) - This term refers to the total liquid flow through a porous medium; for example, a clay liner.

seepage flux - Volumetric flow rate of seepage in a porous medium per unit cross-sectional area. In a clay liner flow domain, the seepage flux has the same value as the Darcian velocity.

sorption - The action by which the molecules of one substance are taken up and retained by another substance, as by the process of adsorption or absorption.

suction potential - Same as potential except that the word "suction" is used to emphasize the negative sign of the potential or pressure.

Unified soil classification system - The unified soil classification system identifies soils according to their textural and plasticity qualities, and their grouping with respect to

their performances as engineering construction materials. The soils are divided as (1) coarse-grained soils, (2) fine-grained soils, and (3) highly organic soils. The coarse-grained soils are subdivided into gravels (G) and sands (S). Fine-grained soils are subdivided into silts (M) and clays (C), depending on their liquid limit and plasticity index.

ML - inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity.

CL - inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays.

OL - organic silts and organic silty clays of low plasticity.

MH - inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts.

CH - inorganic clays of high plasticity, fat clays.

OH - organic clays of medium to high plasticity, organic silts.